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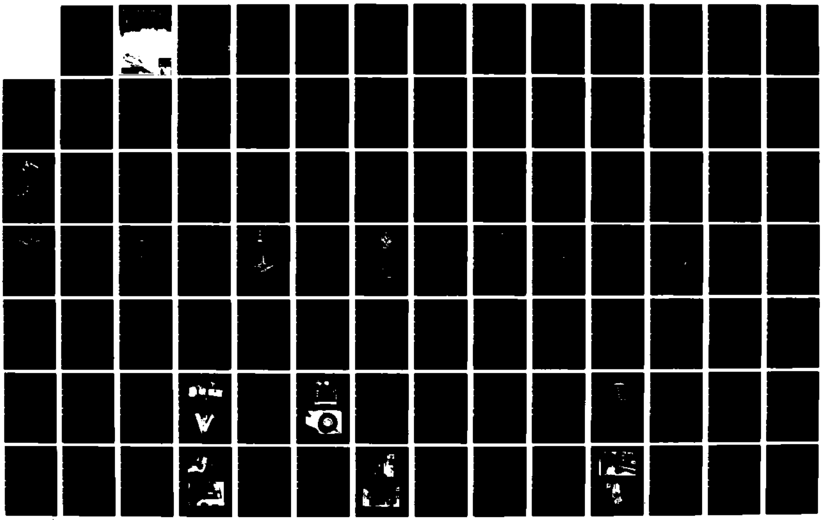

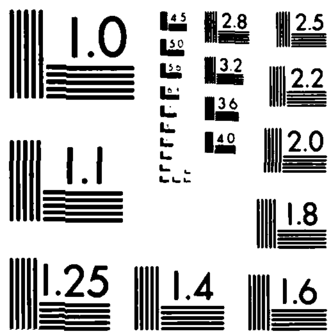

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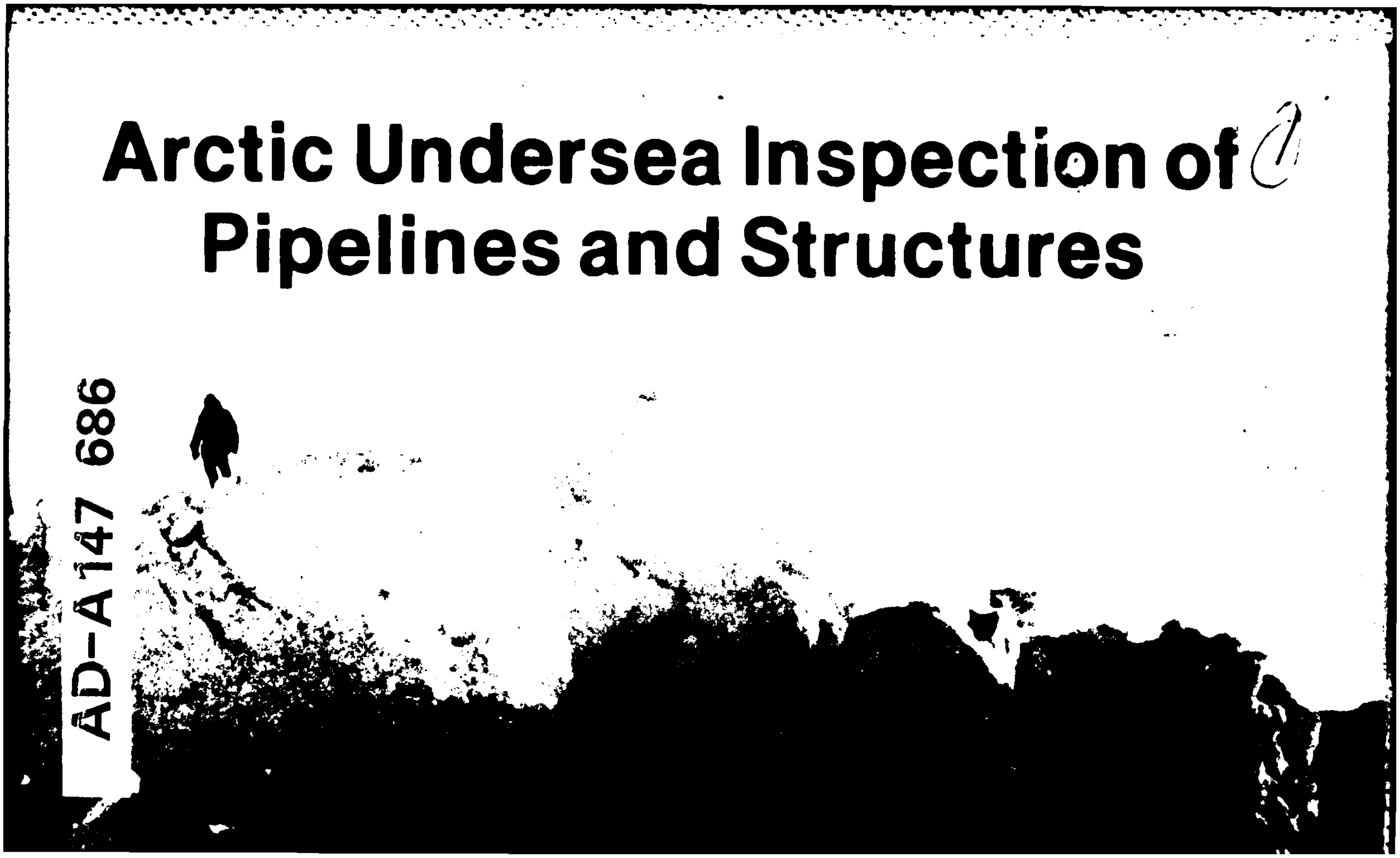
Arctic Undersea Inspection of Pipelines and Structures



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ARCTIC UNDERSEA INSPECTION OF
PIPELINES AND STRUCTURES

June 1983

Conducted by: Busby Associates, Inc.
576 South 23rd Street
Arlington, VA 22202

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PREFACE

The Arctic Ocean is estimated to hold petroleum reserves equal to all of the remaining world reserves. Extraction of these reserves from Arctic coastal, on-shore fields has been taking place for several years. The 1970's witnessed accelerated efforts in offshore exploration drilling which is currently being conducted in the Canadian and U.S. areas of the Beaufort Sea and the Canadian High Arctic Islands. Although offshore Arctic production has not yet taken place, it is estimated that it will begin in earnest before the close of this decade. The severe Arctic enviroment calls for a variety of platform designs and pipeline protection techniques unique to the Arctic. The severe enviroment also calls for underwater inspection programs quite unique from those which are being conducted in more temperate, ice-free latitudes. Such programs are necessary to assure uninterrupted production, human safety and minimal impact on the hostile, but, delicate, Arctic enviroment. The purpose of this study was threefold and concentrated in the areas of: 1) inspection requirements; 2) equipment performance and 3) research and development. Inspection requirements sought to : 1) Identify current and/or proposed undersea inspection requirements of governments and oil and gas operators with interests in the Arctic; 2) ascertain those components or aspects of Production Platforms, Loading Terminals, Production Risers and Pipelines which are considered critical (i.e., vulnerable) to Arctic conditions, and 3) define the enviromental conditions under which present inspections are being conducted and under what conditions might near-future (through 1990) inspections be anticipated. Equipment performances are aimed at 1) describing the tools and deployment techniques which are now being used to carry out present Arctic and sub-Arctic inspections, and the techniques used to position these devices: divers, manned submersibles, remotely operated vehicles; 2) determine the degree to which present inspection techniques satisfy present requirements, and 3) evaluate the degree to which present devices and techniques will satisfy future anticipated requirements. Research and development sought to: 1) identify and describe national and international Arctic research and development programs being pursued to conduct present and fulfill future undersea inspection requirements; & 2) the degree possible, describe the Non-Destructive Examinations necessary for present and future undersea structures.

The data for this study were collected through literature reviews, telephone interviews and personal visits to offshore oil operators, government activities involved in writting inspection requirements and users and manufacturers of underwater inspection equipment in the United States, Canada, England, and Scotland. Written correspondence was used to contact certification activities and equipment suppliers in Norway, Sweden, West Germany, and Denmark. The personnel contacted are listed in Appendix III and the sources of published information consulted are contained in Appendix II. The program began in July 1981 and concluded in July 1982.

ACKNOWLEDGEMENTS

This study is a result of the wholehearted cooperation of the over 100 people and offices tabulated in Appendix III. We are grateful to them for having freely given their time and knowledge to our efforts. Several individuals were particularly cooperative, and their contributions introduced a great measure of practical experience into the observations made herein. To the following we extend our appreciation and gratitude: Phil Nuytten, President, Can-Dive Services, Ltd.; Bill Belsey, Can-Dive Services, Ltd.; Geoffrey Nunn, Brown and Root, Inc.; Ken Paddock, Pipeline Inspectorate, UK Dept. of Energy; David Partridge, Offshore Supplies Office, UK Dept. of Energy; Alan Judge and Raymond Smith, Department of Energy Mines and Resources, Canada; C.A. Lewis, Department of Indian and Northern Affairs, Canada; George Alers, Magnasonics, Inc.; Ron Geer, Shell Oil Co.; and T.K. Thompson, T. Thompson, Ltd. Particular thanks and appreciation are given to Elizabeth Norton, who assisted in much of the research and typed the entire manuscript with great enthusiasm and cheerful demeanor.

EXECUTIVE SUMMARY

Arctic Oil and Gas Activities

The Arctic, according to one source, is estimated to contain oil resources in the neighborhood of 500 billion barrels, an amount equal to the total known reserves of the entire remaining world. Beneath the U.S. Alaskan Arctic Ocean the Dept. of the Interior estimates 2 billion barrel reserves (95% probability) and, between this area and the Bering Sea reside a total of 27 billion barrels (5% probability). Five countries border the Arctic Ocean shores: the U.S., Canada, Greenland, Norway and the USSR. Although Arctic drilling began as far back as 1920, offshore drilling did not begin until the 1950's. From the fifties onward Arctic offshore drilling has continued at an accelerating pace. Today there are over 16 companies actively engaged in Arctic offshore oil and gas exploration; they are confined at present to the relatively shallow waters of the Canadian and U.S. Beaufort Sea. Only one oil production system has been installed in Arctic waters, a wet subsea system which is currently not operating. Estimates concerning the data for future full-scale oil and gas production from the U.S. and Canadian Arctic offshore areas vary and are dependent primarily upon economic, political and environmental considerations. The most optimistic esimtates look to the mid-1980s, but most operators consider the late eighties as most likely.

Marine Environment

The Arctic marine environment imposes unique boundaries upon the type of production platforms and the installation of oil and gas transmission pipelines which may be employed. Consequently, the nature and scope of underwater inspection techniques which can be employed are, while not necessarily unique, somewhat restricted relative to other ocean areas. The water column environment of the Arctic is in many respects less hostile than other marine environments where oil and gas production is currently underway. Water visibility ranges from 3 to 4m annually except for local areas off the mouths of major rivers. Water temperatures, although cold (-1.5°C minimum) are not restricting to any present form of underwater intervention. Measured currents show 60cm/sec (1.2 knots) maximum and 20 to 40 cm/sec (0.2 to 0.4 knots) generally prevailing. Sea states are generally calm (owing to the ice cover) and rarely exceed 2 to 3 except during storms in the ice-free season. Marine fouling organisms, an anathema to inspection in all other ocean areas, have not been a problem in present Arctic operations. Unique Arctic problems are ice movement and its destructive force on surface structures and gouging effects on bottom sediments and sub-bottom structures. Also unique is the presence of permafrost in Arctic Ocean sediments. Arctic climatology imposes severe operating conditions. Above freezing temperatures occur less than 60 days annually along the Beaufort Sea coast and wind chill factors of -45°C and greater are not uncommon. Ice-free conditions occur for periods from 4 weeks to 3 months depending on the location; consequently, the weather window for logistical support and platform inspection, maintenance and repair is the briefest of any ocean area. Personnel and supplies are obtained from sources some thousand miles distant and rely for the most part on air transportation. In essence, underwater inspection in the Arctic, although not demonstrated in certain Arctic environments, appears to be technically within the state-of-the-art, but it will always be difficult to conduct and support.

Platforms and Pipelines

Production platforms in the Arctic offshore will assume many varied configurations which are suitable for specific environments. Present drilling platforms, which are candidates for future production platforms, are ice islands (water depths to 3m); artificial gravel or earth islands (water depths from 5 to 19m) and drillships for waters beyond 20m and up to 260m depth and greater. Concepts for future production platforms include ice islands and artificial earth islands, but also envision underground tunnels, cones and monocones, floating caissons, and wet and dry subsea production systems. In terms of underwater inspection conceptual Arctic platforms are unique in that all critical components, such as risers, cables, sacrificial anodes, support members, etc., will be contained within an ice-protective shell or column. Consequently, inspection may be carried out within the shell under less harsh conditions than on open-framework structures. Arctic pipelining procedures confront unique problems. Gouging by ice will require pipeline burial deeper than now being conducted elsewhere - possibly to depths of 5 or more meters below the bottom. In some instances tunnels, instead of conventional trenching/burial techniques are envisioned. Pipeline insulation will be required to prevent melting of the permafrost. In many instances some of the concepts envisioned for Arctic production platforms will result in inspection programs pursued along lines identical to on-land programs, this is particularly true of artificial earth islands and ice islands. Pipelines, however, will require unique marine approaches.

Inspection Requirements

Underwater inspection requirements for Arctic structures and pipelines can be met by present techniques with two exceptions. One being a U.S. requirement that pipelines which are suspected of leaking be monitored by aircraft overflights of the pipeline route to look for surface evidence of leakage. An ice cover negates this approach. The second exception is the requirement to regularly monitor the cathodic protection system of pipelines. Current monitoring techniques for sacrificial anodes will not be effective for deeply buried pipelines. Specific Arctic underwater inspection requirements have not been specifically addressed by any country. The major problem lies in the uncertainties regarding the Arctic environment. Two major areas of uncertainty are: 1) the frequency and severity of ice gouging and 2) the distribution and sensitivity of the permafrost. Until these phenomenon are fully understood the installation, protection and insulation of Arctic Ocean pipelines cannot be firmed. Until these aspects are firmed, a realistic inspection or monitoring program cannot be developed. Oil and gas operators are aware of and concerned with the eventual need for a comprehensive and practical underwater inspection program. But at this point in time they feel that it is somewhat premature to develop such programs until final designs have been selected for production platforms and pipelines. This view is shared by many individuals with pertinent interests in U.S. and other government regulatory activities.

NDE Devices and Deployment Techniques

The devices and techniques available to conduct Arctic underwater inspection are many and varied. The inspection tools come under the broad heading of Non-destructive Examination (NDE) devices. The techniques for their deployment

include: divers (saturated and non-saturated), Remotely Operated Vehicles (ROVs), manned submersibles (1-atmosphere, untethered; atmospheric diving suits, and observation/work bells) and intelligent pipeline pigs. NDE devices which examine a pipeline or structural member externally, (that is, from the outside looking inward into the component) are dominant. Devices, such as pipeline pigs, which examine the member or pipeline from the inside looking outward, find more frequent application on land. External inspection of structures is aimed at locating and measuring bent or broken members, cracks, debris, corrosion-protection (c-p) effectiveness, foundation scouring and variations in member or riser material thickness. Pipeline external inspection seeks to locate and assess mechanical damage brought about by anchor dragging or trawlers, suspended sections, missing concrete or insulation coatings, c-p effectiveness, and material thickness measurements. Internal NDE of pipelines and risers using intelligent pigs can reveal the extent of irregularaties present in the body wall of the pipe and caused by product corrosion. All of these devices and techniques are suitable for Arctic application with little or no modification.

Overall performance of present NDE devices range, according to the source, from adequate to inadequate. A major complaint has been that virtually all of the devices are adaptions of shore techniques to the underwater environment, a practice with inherent shortcomings. Other inadequacies include: cumbersome equipment, too much reliance on divers untrained in NDE, inadequate fault detection capabilities, little repeatability in measurements, inordinate time required to prepare the surface to be examined (i.e., cleaning) and a wide variety of other minor and major capability problems. Adding to the uncertainties of the NDE device and its data are the problems encountered by the techniques used to deploy them. The diver is strong in the areas of viewing, manipulative dexterity, on-site maneuverability, equipment reliability and responsiveness. His weakness are in his lack of NDE training, payload, transiting capability, depth capability and an unknown degree of judgement degradation brought about by the psychological aspects of diving exposed to a cold, dark, lonely environment. The ROV, on the other hand, presents no danger to the inspector and operator, it has unlimited operating duration, depth capability and transiting distances and its results are presented in real-time which can be viewed by an almost unlimited number of qualified inspectors. Conversely, the ROV only presents a two-dimensional view, its manipulative capabilities are no where equal to the diver or to many NDE tasks, it is subject to cable fouling and rupture and can be very unreliable in terms of equipment performance. Each deployment technique, whether it be diver, ROV or manned vehicle has its inherent shortcomings, for this reason most major inspection companies have one or several of each type of device available to conduct a particular NDE task. Pipeline pigs are similarly accompanied by strengths and weaknesses, the latter includes limitations in pitting depth measurements, weld interference with defect measurements, inability to measure certain longitudinal defects and the laborious chore of manually interpreting the resultant records. Paramount is the possibility of the pig becoming stuck in the pipeline, a circumstance involving extraordinary location/removal efforts in a pipeline in deep water. In spite of the many and varied problems and shortcomings in present NDE devices and deployment techniques, they do provide a capability for detailed and general inspection of structures and pipelines throughout the world oceans, including the Arctic.

Current Research and Development

Current research and development related to underwater inspection of Arctic structures and pipelines are limited and aimed at objectives other than inspection. The objectives, if gained, will provide either devices, techniques or vehicles which can enhance Arctic inspection capabilities. The majority of R&D involved in underwater inspection is not specifically Arctic-oriented, but the results can be applied to Arctic inspection and, therefore, are of importance to this study. The following is a brief synopsis of these programs.

Direct Arctic Programs

Program: DIVING MOSQUITO
Participants: Kockums Shipyard; The Norwegian Underwater Institute
Objective: To develop a 350m depth capable habitat to support most types of underwater work and can be tailored to conduct inspection, repair and maintenance of pipelines, risers and subsea completion systems. The habitat, designated the DIVING MOSQUITO, displaces 900 tonnes and will support 16 divers and 8 to 12 crew members for up to 14 days. An onboard propulsion system will enable it to maneuver within a limited area in up to 2 knots of current.

Program: Polar Gas Project
Participants: Polar Gas, Monenco Pipeline Consultants, R.J. Brown and Associates and Can-Dive Services, Ltd.
Objective: To demonstrate the technical feasibility of connecting sections of 91cm diameter pipeline in 503m of water. Initial tests consist of mating two sections of pipe on the sea floor using mating sleds and procedures developed by Brown Associates. The sections will be welded using a 1-atmosphere welding habitat and support devices designed by Can-Dive Services. The point of this demonstration is to show that similar tie-ins can be accomplished in the McClure Strait and Byam Martin North Channel in the Arctic Islands. The welding habitat will be used to conduct the welding and, among other tasks, perform NDE of the welded joint consisting of ultrasonic and radiographic inspection.

Program: Underice Profiling
Participants: Marine Systems Engineering Laboratory, University of New Hampshire supported by the Minerals Management Service
Objective: The program addresses the generic problems involved in performing a long range (possibly 1800km) underice inspection mission. Initially a 10km mission will be attempted which takes acoustic profiles of the ice keel and the bottom employing six echo sounders (five upward looking and one downward looking). A large part of the program will entail investigating vehicle control to assure a high degree of reliability. The program will attempt to implement high level languages into the system. It is also hoped to develop a recording device for the vehicle that will store engineering data and operating parameters during testing, as well as very large quantities of data during the mission.

Program: Autonomous Remotely Controlled Submersible (ARCS)
Participants: International Submarine Engineering, Ltd. supported by the Bedford Institute of Oceanography.
Objective: To develop an autonomous vehicle for conducting bathymetric surveys in the high Arctic during ice-free conditions. The performance goals of this vehicle are: an endurance of 180km, a speed of five knots maximum and a maximum distance from the control station of about 18km. It is hoped to eventually broaden the instrumentation suite to include seismic and side-scanning sonar.

Program: Conventional NDE
Participants: Dome Petroleum; Can-Dive Services, Ltd.
Objective: Dome Petroleum is utilizing divers and mpi to examine the submerged hulls of four drillships, the first of which has been drilling since 1976 in the Beaufort Sea. The plan is to begin drydocking the ships in the near future at the rate of 1 per year. The hulls will be re-examined by mpi and other techniques in drydock and the results will be compared against those obtained through underwater techniques.

Inspection Programs with Arctic Application

R&D programs in this category are many and varied. For a full description of the participants and objectives consult Section 7.2.

Instruments/Tools

Closed-Circuit TV: Develop an improved form of wide-angle, full color display covering a field of view of 180 degrees horizontal by 60 degrees vertical coupled with a high-resolution center of interest presentation of about 8 degrees.

Underwater Acoustic Television System: Utilization of high-resolution acoustic imagery for inspection in turbid water.

Ultrasonic Torch: Development of a diver-held, acoustic flaw detection device to rapidly detect, locate and record surface-opening cracks above a pre-determined size when wearing cumbersome diving gloves.

Holography: Conceptual development of flaw device utilizing lasers.

Techniques

Flooded Member Detection: Development of an acoustic technique for rapidly determining whether or not a structural member is flooded without the need for prior cleaning.

Pipeline Leak Detection: Development of acoustic (active and passive) and direct visual techniques for locating pipeline leaks.

Project Mass: Intergration of off-the-shelf components to provide a system for correlating and identifying videotape records for cross-referencing with navigation and survey (i.e., inspection) data.

Vibration Analysis Monitoring: Investigation of global and local modes of vibration analysis to ascertain the integrity of a structural member.

Acoustic Emission Monitoring: Development of a portable system to identify and monitor crack propagation via acoustic monitoring techniques.

NDE Round Robin: To determine the applicability of a variety of NDE techniques for determining the structural integrity of fixed structures.

Vehicles

EAVE East and West: Development of an autonomous (untethered) ROV and sensor systems for pipeline and structure inspection.

Foundation Mattress Inspection System: To fabricate a bottom-crawling ROV for acoustic and visual inspection of mattress foundations in waters of less than 10cm visibility.

Marine Maintenance Inspection Machine: Development of a tethered ROV designed specifically and uniquely for inspection of offshore structures.

ARGYRONETE: Construction of a long duration (14 days), long range (850km) lockout submersible capable of transporting and supporting 10 crew members (4 divers) to depths of 300m.

PHOENIX Program: Development and fabrication of two lockout submersibles and one submarine powered by a closed-cycle diesel engine and capable of supporting upwards of 11 divers for 10 days at depths to 500m.

Recommended Research

Specific recommendations for research which will result in new NDE devices or improvements to existing ones to Arctic undersea inspection requirements are, at this point in time, difficult to define. The problem is threefold: 1) although present equipment appears suitable for Arctic application, definitive assessments are impossible until they have been used in the Arctic where unique problems, now unforeseeable, may develop; 2) until designs for production platforms and pipeline protection technique have been firmed, it is impossible to specifically identify deficiencies in the performance of existing NDE techniques, and 3) until more definitive information is obtained from the Arctic marine enviroment, particularly the frequency, sites and depth of ice gouging and ice forces, and the extent and location of permafrost, structural designs cannot be finalized.

Regardless of the many uncertainties regarding Arctic inspection requirements, there are certain areas in which knowledge is sufficient to present recommendation for research. Three unique factors of the Arctic marine viroment offer serious obstacles for conducting underwater inspection through conventional techniques: 1) a short weather window; 2) a permanent and semi-permanent ice cover which can migrate upwards of 24km in a 24 hour period and 3) ice gouging of the bottom which will require sections of a pipeline to be buried, possibly within, and definitly in close proximity to permafrost. A fourth category, overall inspection scenarios, is aimed at improving present NDE techniques for Arctic application and anticipating future Arctic production platform inspection requirements.

Short Weather Window

Several techniques are being investigated which seek to provide a rapid reconnaissance of a structure to identify areas (i.e., members) on the structure which require detailed NDE. Development of these techniques should be pursued because , if successful, they will reduce the time required for deployment of divers, ROVs, etc., and, consequently, accomodate the brief period of Arctic ice-fire conditions which produces completion for access to the platform by a variety of equally necessary support services. Three areas of research appear to provide a possible solution to this problem: vibration monitoring (local mode); acoustic emission monitoring, and acoustic surveillance for flooded members.

Vibration Monitoring: Local mode vibrational monitoring should be investigated to determine the extent to which it can be relied upon and the limits to what it can detect regarding a member's integrity. Once such limits have been identified and a confidence level established, the level of effort for development, improvement or modification of present NDE devices (c-p monitoring, mpi, ultrasonics, etc.,) can be established.

Acoustic Emission Monitoring: Acoustic monitoring utilizing portable instead of fixed sensors is attractive for reasons of expediency, cost and dependability. Research into this area, like vibration monitoring, should seek to establish the limits of the technique and its applicability to Arctic structures as preliminary inspection reconnaissance technique.

Flooded Member Detection: This technique (section 7.2.2.a), if successful establishes the worst case condition: that a member has cracked. Conversly, it also can establish that a crack has not fully penetrated the member, but is superficial in nature. This knowledge can be used in selecting the next type of NDE procedure and the pace at which it need be conducted. The technique should be investigated to determine its reliability and its adaptability to deployment from an ROV.

Ice Cap Migration and Cover: The simple presence of an ice cover precludes satisfying the legal requirement for visual surveillance of the sea surface over a pipeline suspected of leaking. Migration of the ice cap precludes utilization of vehicles or platforms which depend upon a surface-connected umbilical for operation and data telemetry. Two alternatives are available: a manned untethered submersible or an autonomous ROV. For reasons of human safety the manned submersible loses its attractiveness. The autonomous ROV is a recommended alternative for inspection of unburied or shallowly-buried (less than 1m) pipeline.

Autonomous ROV: Research and development of autonomous ROVs such as being conducted in the EAVE west and east programs and the ARCs project should be continued. Development should concentrate within the following areas:

- improved energy source to permit continuous operations for a minimum of 24 hours
- vehicle positioning to at least $\pm$ 3 m. at any point on the pipeline
- magnetic pipeline following capability, to hold the vehicle within optical viewing range (1 to 3 m.) of the pipeline

- Instrumentation development to include:

  video observation and tape storage
  stereophotogrammetric camera system
  leak detection sensors (for oil and gas)
  remote c-p monitor capability (current density field)
  pipeline insulation integrity monitory (e.g., infrared technique, thermal measurements)

- Deeply Buried Pipelines

Intelligent Pipeline Pigs: The most practical solution to inspection of pipelines buried 5 or 6 m. below the sea bottom is pigging. Many deeply-buried pipeline problems are anticipated, owing to the protection of the overburden, to originate from factors internal to the pipeline instead of external factors such as anchor or trawl damage, suspended sections due to scouring, etc.. External factors which might damage or distort the pipeline may arise from ice islands grounded immediately atop the pipe or permafrost which has melted around it. Pigging is the only present technique which can inspect pipelines under 5 or 6 m. if cover without removing some or all of the overburden. The following areas have been identified which call for improvement and/or development in pigging capabilities:

- measurement inaccuracies due to mandrel marks
- pre-knowledge of each pipeline segments wall thickness
- pitting depth measurement limitations
- laborious procedures for grading and analyzing logs
- false readings due to foreign metallic objects
- inability to detect defects less than 7.5 cm.from welds
- inability to confidently measure longitudinal defects, less than 2.54 cm. width
- inability to monitor the effectiveness of external thermal insulation
- inability to monitor the effectiveness of sacrificial anode corrosion protection systems

- Overall Inspection Scenarios

NDE Round Robin: This program, described in section 7.2.2.f, should be continued and expanded to include all potentially applicable NDE techniques for the Arctic. The results should be made available to the underwater inspection community, including those who write inspection requirements, certifying societies and service companies who use the devices.

Artificial Island Inspection: Acoustic techniques, (i.e., side scan sonar) have been used in the Arctic to determine the position of sand bags providing protection to artificial islands. Interpretations of the side scan record is done manually; it is a laborious chore subject to human error. Application of pattern recognition techniques should be investigated to increase the speed and accuracy of the record analysis.

Structure Inspection Techniques: Arctic offshore production platforms are unique, in that, all critical components in previous designs are continued within a shell providing a defensive barrier against ice. Consequently, inspection of the structure may be conducted from inside the structure looking out, instead of the converse as is done on all other non-Arctic structures. It is recommended that production platform designs which appear most likely Arctic candidates be carefully examined to determine the feasibility of conducting inspection of critical components inside the protective shell. This investigation should also look at the feasibility for inspection of the shell itself from the inside.

1.0 THE ARCTIC OCEAN

This discussion of Arctic Ocean characteristics is limited only to those characteristics which have a direct bearing on the conduct of and the potential problems related to underwater inspection. Consequently, many environmentally important parameters, such as nutrients, dissolved oxygen and marine flora and fauna are not discussed since their influence on the tools and techniques in underwater NDE are of minimal importance.

The Arctic Ocean is the smallest of the earth's oceans (14,000,000 km^2) (Fig.1) and is bounded by five countries: the United States, Canada, Norway, Greenland and the USSR. The floor of the Arctic Ocean is quite uneven and is composed of numerous Ridges (Lomonosov, Mid-Ocean, Alpha), Deeps (Canada, Makarov, Eurasia, Fram) and a Continental Shelf ranging from a normal width of 100 to 200 km off Alaska and Greenland to as much as 1700 km off the USSR. The average depth is about 3,600 m; the greatest depth is over 4,800 m. Bounding the central Arctic Ocean are seven seas, these are the Chukchi, East Siberian, Laptev, Kara, Barents, Norwegian and the Beaufort. The Beaufort Sea is currently experiencing the most activity by far of its sister Arctic seas in regards to oil and gas exploration, and, since it bounds the U.S. coast of Alaska, it is of primary importance to this study. Consequently, it serves as the focal point for discussion of Arctic Ocean characteristics.

1.1 Climatology

The following summations are taken from the report Technology Review of Arctic Offshore Oil/Gas Operations, prepared by Energy Interface Associates, Inc. (1979) for the U.S. Geological Survey.

1.1.1 Air Temperature

Persistently low temperatures characterize the Arctic climate. Monthly radiation values vary from near zero during the winter to an average of about 71 kilojoules/cm^2 per month in June (Swift et al, 1974). Consequently, lacking solar radiation, heat input to the Arctic air is primarily derived from long-wave radiation emanating from the surface. As a result, air temperatures offshore and along the coast tend to be somewhat milder and uniform than at inland locations. Air temperatures above the polar pack ice, for example, are not as cold as readings reached in the Alaskan and Canadian interior because of heat radiated by the comparatively warm water below the ice.

Table 1 is a listing of representative temperature information for nine coastal stations along the Chukchi and Beaufort Seas. This Table shows that there are less than 90 days on which temperatures are above the freezing point all locations, and less than 60 days along the Beaufort Sea coast.

1.1.2 Precipitation

Precipitation over most of the Arctic coast is usually less than 25 cm. annually in the Beaufort and northern Chukchi Seas. Rain accounts for the major part of the annual precipitation. (Table 2) Snow may fall during

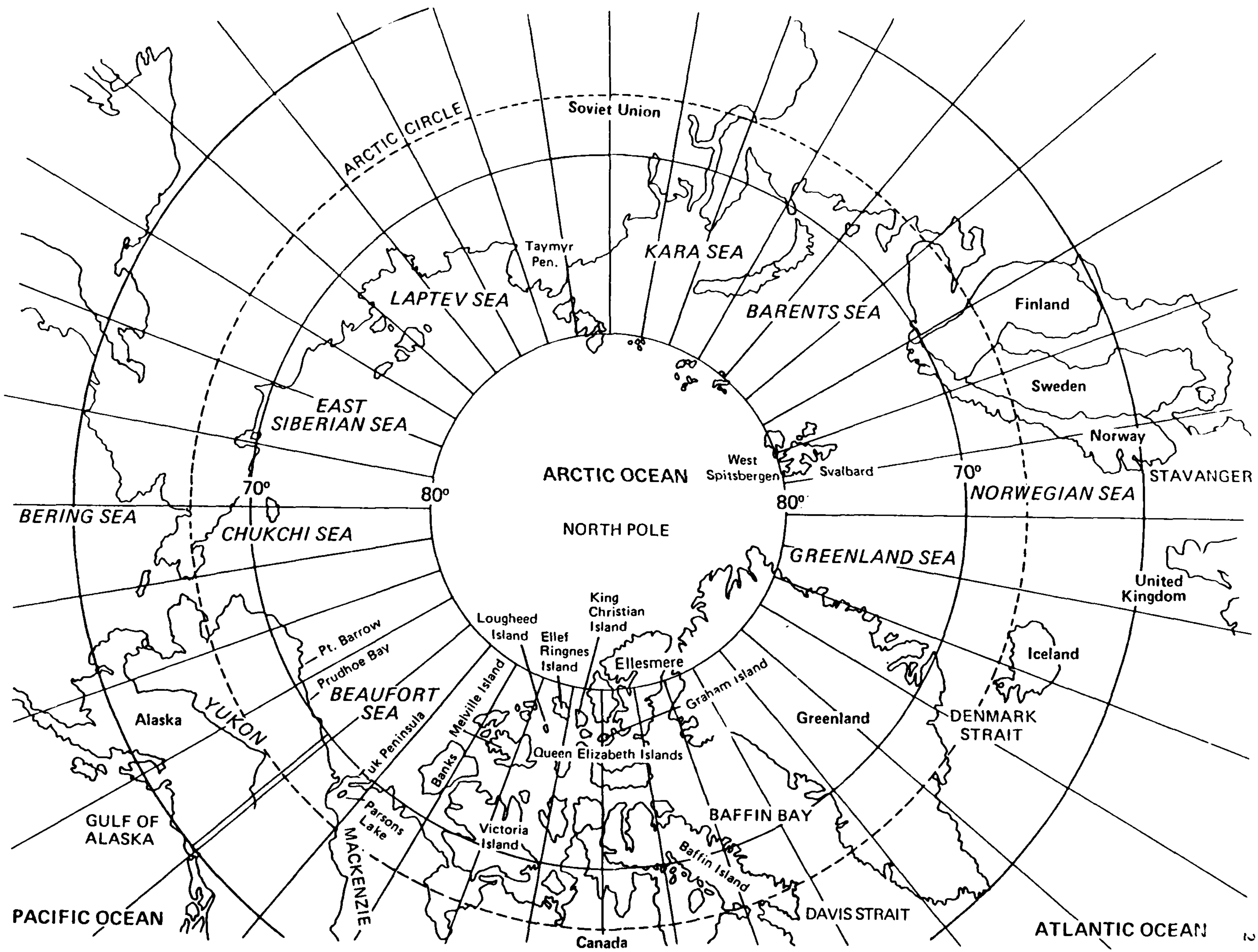


Fig. 1. The Arctic Ocean.

TABLE 1. Arctic Coastal Temperatures

Station	Mean[1] Annual °C	Summer[2] Season. Max. °C	Winter[2] Season. Max. °C	Record[1] High °C	Record[1] Low °C	Mean No. of Days 0°C and Below[2]
1. Tin City	-6.7	10.0	-23.9	23.9	-42.2	---
2. Kotzebue	-6.2	16.1	-24.9	29.4	-46.7	251
3. Cape Lisburne	-7.8	11.1	-28.9	23.3	-43.9	268
4. Point Lay	-10.6	11.6	-32.7	25.6	-48.3	284
5. Wainwright	-11.8	10.0	-31.1	26.7	-48.9	306
6. Barrow	-12.6	7.2	-31.1	25.6	-48.9	324
7. Lonely Point	-12.6	---	----	25.6	-47.2	---
8. Oliktok	-12.9	---	----	23.9	-45.0	---
9. Barter Island	-12.2	8.9	-32.2	25.6	-50.6	311

[1]Data from Brower *et al*. (1977)

[2]Data from Swift *et al*. (1974)

TABLE 2 Arctic Coastal Precipitation[1]

Station	Liquid Precipitation (Centimeters)				Snow (Centimeters)		
	Annual Mean	Monthly Maximum	24-Hour Maximum	Mean Number of Days = .01 or more	Annual Mean	Monthly Maximum	24-Hour Maximum
1. Tin City	48	19.5 (Aug)	5 (Jul)	143	190.5	62.5 (Sept)	21.5 (Apr) (Sept)
2. Kotzebue	20.5	13 (Aug)	4.5 (Jul)	110	119	153.5 (Jan)	21.5 (Mar)
3. Cape Lisburne	37	17 (Aug)	4.5 (Aug)	---	152	----	27.5 (Nov)
4. Point Lay	16.5	15.5	3.5	---	50.5	----	----
5. Wainwright	12.5	23.5 (Aug)	10 (Jul) (Aug)	---	30	30 (Oct)	---
6. Barrow	10.5	7 (Aug)	2.5 (Oct)	74	73.5	66 (Apr)	38 (Oct)
7. Barter Island	16	12 (Sept)	5.5 (Jul)	93	116.5	91 (Sept)	43 (Sept)

[1]From Swift et al, 1974

any month of the year and the ground is normally snow covered from mid-September until June. Total annual snowfall averages 30 to 152 cm along the North Slope coastal stations. To the south, snowfall increases to a maximum of 50 to 177 cm in Kotzebue Sound.

1.1.3 Surface Winds

Surface winds along the Arctic coast tend to blow at a fairly constant rate throughout the year. Yearly means of 16 to 24 km are typical of all exposed coastal locations and completely calm conditions exist less than 5 percent of the time at most coastal stations. Table 3 summarizes surface wind conditions for stations along the Beaufort and Chukchi coasts.

High winds may occur at any time of the year although maximum velocities have occurred historically in the coldest months.

The persistent Arctic wind can pose a number of operational difficulties. Wind chill, and its resultant effects on humans, is probably the most serious problem. A wind chill of minus 45°C, such as can occur at Kotzebue, can freeze exposed flesh within one minute. In addition to driving the snow as it falls, thus creating visibility problems, strong winds also form deep drifts which hamper surface transport. Wind may also cause a number of ice-related problems. During the summer months, for example, strong offshore winds may drive the pack ice into the nearshore area. This occurs occasionally east of Point Barrow and seriously interrupts the summer barge and shipping routes along the North Slope.

1.2 Oceanography

1.2.1 Ice

Ice is the major dynamic factor influencing Arctic undersea inspection. The extent, thickness and migration rate of the ice cover determines the type of instrument deployment technique which can be employed; when it can be deployed and how it can be deployed. The keel depth and subsequent bottom-scouring depth (i.e., gouging) and transient loading of the seabed by drift-ice ridges will determine the safe burial depth of pipeline. It will determine the potential application of conventional NDE techniques toward remote inspection of buried pipelines. Two types of ice have been identified in the Arctic: pack ice and landfast ice.

1.2.1.a Landfast Ice

The landfast or bottom-fast ice occurs in a zone adjacent to the coastline and restricted to depths of approximately 2 m. Inside the 2m depth contour the landfast ice rests on the bottom at the end of the seasonal growth and is generally stable throughout the winter. While the landfast ice zone is generally thought of as stable, several investigators report lateral displacements from several tens of meters to upwards of 100's of meters due to storm winds, and in the early winter and late spring when the ice is forming and deteriorating, respectively.

Just offshore of the landfast ice and extending seaward for varying distances, depending on the season, is a zone of fast ice. The seaward boundary of the floating fast ice is difficult to precisely define. Weaks and Ruser (1980)

TABLE 3. Surface Winds at Arctic Coastal Stations[1,2]

Station	Winter Prevailing Direction	Winter Mean Speed (km)	Summer Prevailing Direction	Summer Mean Speed (km)	Fastest Kilometer Direction	Fastest Kilometer Speed (km)	2nd Fastest Kilometer Direction	2nd Fastest Kilometer Speed (km)
1. Tin City	E, NE	32.18	N, S, SE	24.13	NW	104.58	Several	101.36
2. Kotzebue	E, SE, NE	20.91	W	20.91	SE	149.63	SE	141.59
3. Cape Lisburne	E, SE	20.91	E, NE, SW	19.30	---	104.58	---	88.49
4. Wainwright	E	---	E, SW	---	---	---	---	---
5. Barrow	E, NE	17.69	E	19.30	W	93.32	W	88.49
6. Barter Island	W, E	22.52	E, NE	19.30	SW	130.32	W	125.50

[1] Swift _et al_, 1974

[2] see also, _Climatic Atlas of the OCS Waters and Coastal Waters of Alaska_, _Vol. III_, _Chukchi - Beaufort Sea_, 1977 USDOI-BLM-OCSEAP

suggest that the limit be placed at the 13m isobath, although they cite recent studies which have observed it at depths in excess of 20m. Within this shear zone pressure ridges are developed which, upon grounding, act to anchor and stabilize the landfast ice. During the late fall and winter new ridges join and adhere to the initially developed and grounded features such that by the end of winter a wide zone of grounded sea ice ridges (the "stamukhi" zone) occurs between the 10 to 30m isobaths (C.F.M. Lewis,1981). The landward portion of the stamukhi zone remains in place during or well into the subsequent melt season and the entire zone will generally not exceed 100km in width. The seaward portion of the zone consists of highly deformed and drifting ice. Also in this zone are moving masses of cold, thick first-year ice and first-year pressure ridges.

1.2.1.b Pack Ice

Centered at about 80° N latitude and 150° W longitude and with a radius of some 1000km is the permanent polar pack ice. This is a vast assemblage of ridged and hummocky ice floes averaging 4m thickness and composed largely of multi-year ice. The entire polar pack rotates clockwise about its center and makes a complete revolution approximately once every 7 to 10 years. At the southern rim of this "Beaufort Gyre", the ice drifts westward at an average rate of 2.5km/day (1-5 km/day), but has been reported to move as much as 25 km/day in the spring (Offshore Engineering, Dec. 1979, p. 43).

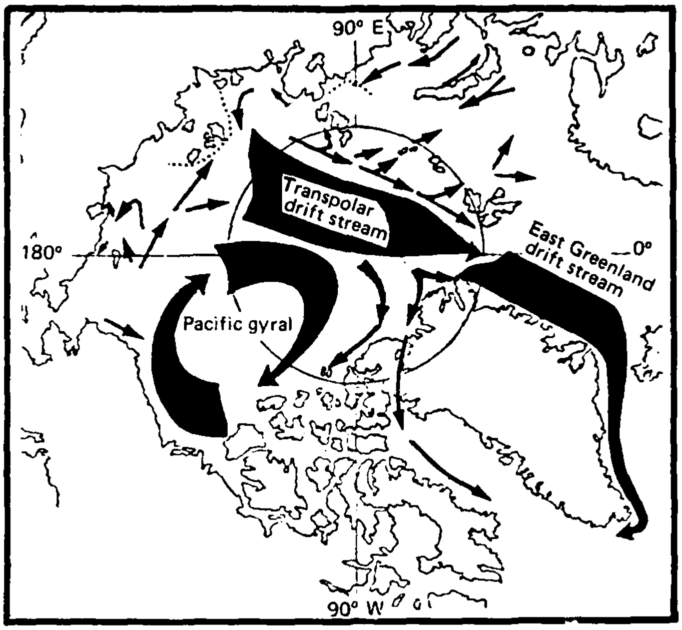
Ice located seaward from landfast ice is also known as pack ice, but it may be formed in seasonally open waters and is designated as seasonal pack ice. Seasonal pack ice develops out to a distance of 100 to 200 km, or roughly to the edge of the continental shelf in the Beaufort Sea, which is between 400 to 1000m deep (Pallister and Pallister, 1978). Polar pack ice migrates southward in the fall into the Beaufort Sea area when winds push it into the seasonal pack ice and creates pressure ridges in what is termed the "transition" zone. (Fig.2) These ridges may be embedded in heavy multi-year floes and have an average thickness of up to 5m. Keel depths of up to 47m have been reported (Weaks and Rosen, Ibid.) The boundary between landfast ice and the seasonal pack ice is likewise deformed and heavily ridged and is known as the active shear zone. Even in winter conditions as much as 5 percent of the ice pack may be open water consisting of leads and polynyas.

1.2.1.c Ice Islands

Tabular icebergs produced by the calving of ice from the Ellsmere Ice Shelf have been designated as "ice islands." Typical lateral dimensions of ice islands are from 30 to 100m and thicknesses of 12 to 30m and are most commonly found off the North Slope of Alaska. Upon forming, an ice island drifts southwestward along the coast of the Canadian Archipelago and northern Alaska. It may enter the Transpolar Drift Stream and leave the Arctic within three years, or it may enter the Pacific Gyre and circulate for decades. (Kovacs and Mellor, 1974). According to Weaks and Rosen (1980) little quantitative information exists concerning ice island size distribution, numbers, degradation rates and production rates.

1.2.1.d Ice Gouging

Ice keel gouging or scoring of the seabed is currently under intense



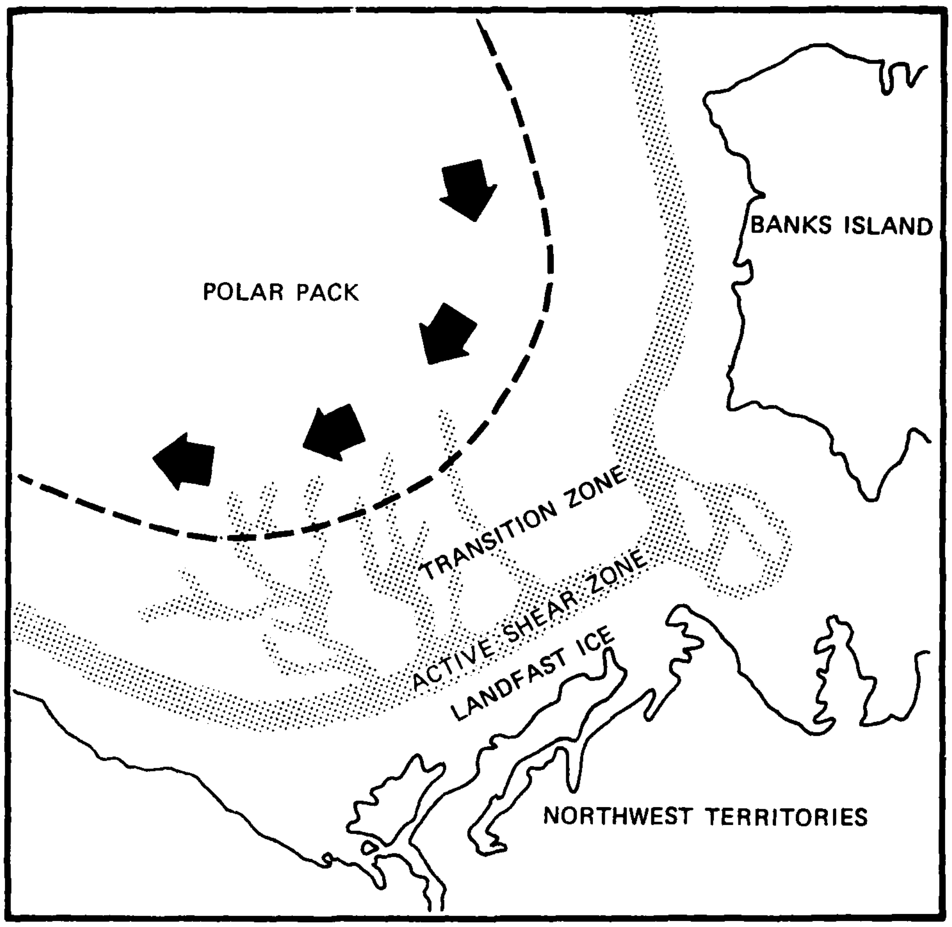


Fig. 2. Top: Major polar drift streams.
(from Kovacs and Mellor, 1974)

Bottom: Ice and ice zones in the Canadian Beaufort Sea. (from Pallister and Pallister, 1978)

investigation owing to its obvious relationship to pipeline depth-of-burial and to the less obvious dynamic loading effects grounded ice masses would exert on buried pipelines

Gouging is caused by grounded pressure ridge keels and ice island fragments being propelled by winds and currents. The frequency of gouging and the age of existing gouges is uncertain. Also, owing to the recent increased activity in this area, observations concerning gouge depth and the depth of water in which gouging occurs do not uniformly agree.

Two publications (Pallister and Pallister, 1974; Offshore Engineering, 1981) state that 50m water depth is the seaward limit of ice gouging. Most investigators seem to agree that the average depth of gouges is less than 1 meter (Lewis, 1981; Offshore Engineering, 1981, and Reimmitz and Barnes, 1974). Lewis, (ibid,) and Pallister and Pallister, (ibid.) state that the maximum gouge depth located to date has been as follows: Chukchi Sea: 4.5m (in 38m of water depth); Alaska sector of the Beaufort Sea: 5.5m, and in the Canadian sector of the Beaufort Sea (North of the Mackenzie Delta): 6.5m. Offshore Engineering (1981) reported rare occurrences of gouges with depths of 7.5m and one unverified gouge of 10m depth. The maximum observed ice keel depth in modern times is 47m. One Canadian Arctic operator, Dome Petroleum, installs its wellheads, which will be in water depths less than 47m, in depressions called "glory holes". The glory holes are dredged so that the top of the BOP is at least 4m below the sea floor, but are for short term protection only.

The presence of ice obviously affects the length of time and the location in which present drilling operations can be conducted. No drilling has been conducted to date in the area of the permanent polar ice cap. The majority of offshore drilling has been conducted in the Beaufort Sea within and between the landfast ice zone and the transition zone. Presently there is an operating window of 110 to approximately 130 days between July and October. Present plans of one offshore operator envisions year-round exploratory drilling by 1982 in non-permanent polar pack ice zone and year-round production in the same zones by 1984. In the permanent pack ice zone the same operator envisions year-round exploratory drilling by 1984 and year-round production by 1987.

1.2.2 Currents

Water currents exert a significant influence on the type of system, i.e., dive bell, ROV or manned submersible, which can be used to carry and deploy NDE equipment. General current (i.e., water circulation) patterns for the Beaufort Sea have been described, but published papers providing specific and detailed current measurements, particularly under ice, are few. The following information, therefore, is not a comprehensive description of the Beaufort Sea current regime, but only a broad overview.

According to O'Rourke (1975), the main features of the Beaufort Sea circulation are shown in Figure 3. In deep waters off the shelf he postulates two layers of circulation: Arctic water (0 to 200m) circulation is dominated by the Beaufort Gyre and moves into the Beaufort Sea at approximately 4cm/sec. Atlantic and bottom water masses appear to move together at velocities less than 3 cm/sec. Mass field computations by Kusnoki (1962) produced the current speed profile presented in Figure 3 which was generated from observations taken

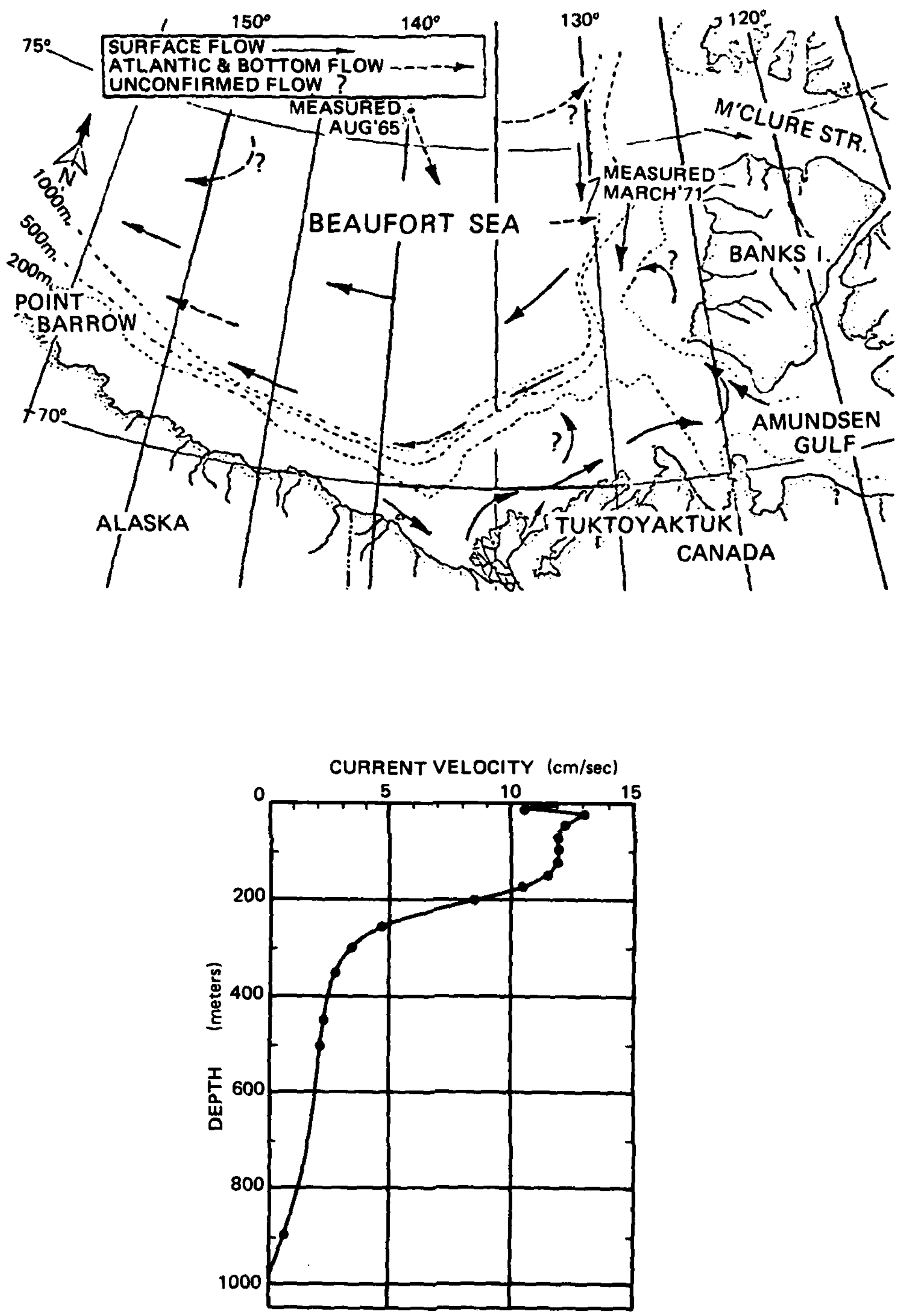


Fig. 3. Top: Horizontal distribution of surface and subsurface water movements. (O'Rourke, 1975)

Bottom: Vertical distribution of current component between T-3 Stations 7-8 (computed from mass field). (Kusunoki 1962)

from ice island T-3 some 192km northwest of Tuktoyaktuk.

During the open water season currents are primarily wind-driven. Measurements taken during the ice-covered season indicate that tides are the principal driving mechanism. Wiseman et al (1974) occupied a 7.5 day current station offshore Pt. Lay in the Chukchi Sea under ice in 15m water depth. The mid-depth data show a mean flow parallel to the shore (northerly) of 2.1 cm/sec (less than 0.05 knot). A subsequent 7.5 day station in the same general location but at 9.8m mid-depth was occupied in July-August during ice-free conditions. These data showed a similar northerly set but a mean speed of 28.1 cm/sec (0.3 knot). Wiseman and his associates believe this greater speed to be a reflection of the influence of directly applied wind stress at the sea surface and also provide current drogue measurements at 2m depth which reinforce this supposition.

Other data show agreement with the above. In the Beaufort Sea Hufford (1975) measured 60 cm/sec (1.2 knots) at 54m depth north of Barrow in the open-water season, as did Aagaard and Haugen (1978) in somewhat deeper waters north of Oliktok and Lonely. Beneath-ice measurements by Barnes and Reimnitz, 1977, and Aagaard and Haugen, ibid., produced current speeds on the order of 10 cm/sec (0.2 knots) or less.

Currents flowing within the numerous straits and channels bounding the eastern Beaufort do not fall under the general characteristics given above. Recent published data (Offshore, May 1980) show currents ranging from 21 cm/sec (0.37 knot) in the M'Clure Strait to over 75 cm/sec (1.6 knots) in the Dolphin and Union Strait, north and south, respectively of Victoria Island. It is likely that other such variances to the overall current region exist at the mouths of major rivers and in other channels and straits bounding the Beaufort Sea.

1.2.3 Water Temperature

There are three main water masses of the Arctic Ocean which have been described by Coachman (1963) and they are identified by the following gross characteristics:

Arctic Water:	0 to 200 m, low salinity, -1.5°C
Atlantic Water:	200 to 900 m, high salinity, greater than 0°C
Bottom Water:	900 m to bottom, high salinity, -0.3°C

Of primary interest to this study is the relatively shallow Arctic water which can be subdivided (O'Rourke, 1975) into a 0 to 50m surface layer and a 50 to 200m subsurface layer. The surface layer varies in thickness depending on melt water, river discharge and wind mixing. In the open water the surface layer becomes comparatively warm in the summer (2 to 6°C) owing to river discharge and solar radiation; it is confined to a thin layer usually not more than 5m deep.

The consequences of these low water temperatures toward underwater NDE impact upon the diver, product (i.e., oil) flow, and equipment performance. The diver, for example, unless protected, has a survival time of 15 to 45 minutes in water of 0°C and below. At 2°C he has between 30-90 minutes and at 6°C between 1 to 3 hours (Searby and Hunter, 1971). Exhaustion or unconsciousness will be reached between 15 minutes to 60 minutes at these temperatures.

1.2.4 Tides

Astronomically induced tides along the Beaufort coast are semi-diurnal with mean ranges of 10 to 30 cm. Tidal ranges in straits and channels bounding the Beaufort can be of greater amplitude and range, for example, in Dolphin and Union Strait from 40cm to as much as 120 cm in the M'Clure Strait.

More significant are meteorologically induced sea level changes associated with wind stresses and barometric pressure differentials. These changes are termed storm tides or storm surges and normally occur with storm systems which originate near the Aleutian archipelago and more northward through the Bering Strait. Storm surges of greatest severity occur during September and October when there are large areas of open water, surges as late as February have been observed but they are normally less severe (Aagaard, et al, 1978). Indirect measurements of storm surge elevations indicate positive elevations of 2 to 3m occurring occasionally along the Beaufort coast.

1.2.5 Waves

The following information was taken from the previously noted Energy Interface Associates report of 1979.

Wave generation by winds along the Beaufort north coast is limited to the summer, open-water season. Since the pack ice retreats a relatively short distance offshore during most summers, the environment is characterized by low, short-period waves except during storms when the winds blow parallel to the coast. Sellman et al (1972) found that 90 percent of the waves in the vicinity of Point Barrow were less than 1m in height. Wiseman et al (1974) made similar observations near Pingok Island and near Point Lay on the northern Chukchi coast. Wave measurements had a characteristic period between 2 and 3 seconds with significant heights (average of the highest 1/3 of the waves) of 20 to 30 cm. Visual observations by numerous sources tend to confirm the mild sea states which normally prevail during summer.

Much more severe waves can occur under certain circumstances. During some summers, for example, the pack ice has been observed to retreat as far as 190 to 260 km off the coast. Under these conditions, severe and rapidly moving storms proceeding across the shelf can generate waves over a relatively long fetch. Carsola (1952) made shipboard observations of average wave heights on the order of 4 to 5m during a storm which occurred near Point Barrow in August, 1951.

Kovacs and Mellor (1974) describe a storm which occurred near Mackenzie Bay in September, 1970. The storm's duration was 36 hours with sustained winds of 104 km hr. apparently produced offshore waves 9m high as judged from visual observations. Work conducted as part of the Canadian Beaufort Sea Project contained a hindcast of wave conditions in Mackenzie Bay (Berry et al, 1977). Results indicated that waves of about 9 or 10m could be expected to occur on an average of once every 50 years in areas having water depths greater than 75m.

1.2.6 Visibility (Underwater)

Visibility varies from season to season, from area to area and sometimes daily. It is at a maximum in the winter and gradually decreases with the advent of spring. Published data concerning visibility is sparse. However,

personal communication with divers from Can-Dive Services reveals that in the Canadian Beaufort Sea the visibility range can be from near 0 to upwards of 15m maximum. Generally 3 to 4m is available during the drilling season which may extend from June through mid-November. Of particular influence on visibility is discharge from major rivers, specifically, in the Canadian Beaufort, the Mackenzie River. During summer months sediments discharged by the Mackenzie have been observed as much as 160 km seaward from its mouth. Under such conditions visibility can be 0, and necessitate utilization of water cones in order for the divers to see, but as a rule of thumb 3m visibility range can be counted on. Man-derived effects in the nature of drilling muds can also induce 0 visibility range, but within a more localized area.

1.2.7 Permafrost

Seabottom sediments with mean annual temperatures less than 0°C are defined to be permafrost materials whether or not inter-granular ice bonding is present (Hunter, et al, 1976). According to Hunter et al pipelines are potentially subject to damage by differential movement of a thaw-bulb which might extend 30m from the pipe or by differential freezing and frost-heave around a chilled pipeline. The impact of permafrost on inspection techniques resides in the potential for requiring some sort of thermal insulation around the pipeline which would preclude the possibility of its increasing the ambient temperature. Such insulation materials may present obstacles to utilizing present or planned NDE techniques and instrumentation.

Two types of evidence reveal the existence of offshore seabottom permafrost in the Beaufort: direct evidence from drilling and indirect or geophysical evidence. Drilling evidence was provided by MacKay (1972) who reported obtaining ice-bonded frozen material from four holes less than 50m below seabottom. Lewellen (1973; 1974) reported frozen sediments along the Alaskan Beaufort coast and Molochuskin (1973) reported the presence of permafrost in water depths of 4m to 900m in the Lapten Sea. McDonald et al (1973), on the basis of shot-hole data, found permafrost within 5m of the seabottom in the vicinity of the Tuktoyaktuk Peninsula. Geophysical evidence for the existence of permafrost has been provided by Hunter (1973) and Hunter and Hobson (1974) from selected areas of the Beaufort Shelf.

On the basis of extensive geophysical data, drilling data and thermal data, Hunter et al (op. cit.) reported that seabottom permafrost exists over much of the Beaufort Sea Shelf with thicknesses from 600m at the shoreline to 100m in the offshore and with the upper boundary occurring at depths between seabottom and 200m below. Significantly, temperatures of sub-seabottom permafrost are much warmer than that occurring on land and ice-bonded sediments are much more susceptible to thermal degradation than their onshore equivalents.

2.0 ARCTIC OFFSHORE OIL AND GAS DEVELOPMENT[1]

The first recorded incidence of drilling in the far North was the Norman Wells, on the Mackenzie River banks, where the first commercial oil was found in 1920 by Imperial Oil Ltd. Lack of demand for the product forced the closing of the well, but it was reopened in the 1930s.

In the 1950s, there was exploration in the lower Mackenzie basin where the river opens into the Beaufort Sea, and in 1959 in the Eagle Plains area of the lower Mackenzie River basin, non-commercial gas was discovered.

The decade of the 1960s prepared the way for the heightened developmental activity of the 1970s. Exploratory drilling by an increasing number of companies, both on and offshore, in the Arctic Islands, in the Mackenzie River and Delta, and in the Beaufort Sea occurred in this period. In 1961-62, Dome Petroleum's exploratory drilling in the Queen Elizabeth Islands tested gas. In 1965, the first well in the Mackenzie Delta in the Beaufort Sea, Reindeer D-27, was drilled to 3,867 m by Gulf Canada Resources and showed the first discovery of gas resources in the area. The well was abandoned in 1966. The first commercial oil field was discovered in Alaska by Arco-Humble in 1968 on the North Slope of Prudhoe Bay, 320 km southeast of Pt. Barrow.

Panarctic Oils Ltd. drilled its L-67 well which showed an estimated two trillion cubic foot reserves in hydrocarbons, the first discovery in the Arctic Islands. Other drilling which occurred in the 60's in all areas of the Arctic was largely developmental.

With the opening of the 1970s, drilling at Atkinson Point on the Tuktoyaktuk Peninsula east of the Mackenzie Delta yielded a significant find. Imperial struck oil, the first in this region. Its H-25 Atkinson well, drilled to 1728m, flowed at rates up to 2800 bod. Its J-17 Mayogiak well on the Tuk Peninsula tested oil and gas at 1158m and 2865m.

Meanwhile, in the Arctic Islands Panarctic drilled offshore at D-18 King Christian, near King Christian Island, and produced a blowout with gas estimated at one trillion cubic feet near the Queen Elizabeth Islands. In the Alaskan Arctic, 28 exploratory wells and 49 developmental wells (with 3 discoveries) were drilled.

More companies were entering the picture, intensifying the drilling effort both on and offshore during the seventies. Esso Resources had 14 drill sites on artificial islands in the Beaufort Sea in 1971. Panarctic's offshore Islands tested gas. Imperial's three wells in the Mackenzie Delta tested gas and oil.

[1]The following information was drawn from a variety of journals, trade publications and reviews which include the Oil and Gas Journal, Arctic Petroleum Operators Association Review, Noroil, American Association of Petroleum Geologists Journal, Offshore, North American Arctic Review, Ocean Industries and special reports issued by Canadian and U.S. government agencies.

In 1972 the offshore drilling activity accelerated in the Mackenzie Delta. From artificial islands in the Delta, Gulf-Mobil tested gas at F-09 Parsons and at P-52 Ya Ya sites; Gulf-Imperial-Shell's K-23 Titalik and F-33 Reindeer sites tested gas; and Shell Explorer Ltd. hit gas and oil respectively at its H-30 Niglintgak and O-13 Kugpik wells. Drilling in the Arctic Islands in 1972 was mainly onshore. BPOG Operations Ltd. tested its first wildcat on Graham Island to 3048m and other companies were drilling on one of about eight other islands.

At the offshore discovery wells, Thor H-28 and Hecla I-69 in the Arctic Islands, Panarctic produced gas in 1973. Imperial's first offshore test in 1973 on the man-made gravel island, B-48 Immerk in the Beaufort, off the Mackenzie Delta, was plugged and abandoned after finding gas at 2707m.

With about 20 rigs operating, the winter season of 1973-74 was the busiest since the beginning of drilling in the Delta and in the Arctic Islands. In that period Panarctic drilled on ice platforms at 12 sites in the Arctic Islands; Suncor, Inc. on two artificial gravel islands in the Beaufort Sea; and Imperial in 2m of water on a new site, F-28 Adgo, an artificial island in the Beaufort designed, unlike Immerk, to subsequently break up.

In 1975, in the Mackenzie Delta, Sun Oil Co., Ltd. drilled its third wildcat, P-04 Garry, from a drillship, testing gas at MMcfd (1 million cu. ft./day). Also, in 1975 Panarctic's offshore discovery well Drake F-76, off Melville Island, drilled to 1127m, and tested gas. Imperial abandoned its B-44 Netserk in the Beaufort Sea at 3400m. On Cameron Island Panarctic's F-72A Bent Horn was readied for production testing of oil from its well which bottomed at 3270m.

Panarctic's offshore discovery wells, W. Hecla P-62 and W. Hecla M-25, near Melville Island both produced gas in 1976, as did its Jackson Bay G-16A discovery well drilled to 1600m off Ellef Ringnes Island.

That same year, Union Oil drilled an exploratory well in 3m of water from a grounded ice island in Harrison Bay, west of Prudhoe Bay. In the Beaufort Sea, Esso Resources drilled in 7m of water at Netserk F-40 which struck oil and gas in 1979 and Dome Petroleum occupied 11 drillsites from drillships and made an oil and gas find in 1979 from its Kopanoar M-13 well begun in 1976. Oil and gas was also discovered at its 1976 Mektoralik K-59 wellsite.

In 1977, drilling continued at the two Dome sites in the Beaufort noted above and began at three others: Ukalerk C-50, Kaglulik A-75, and Nerlerk M-98.

At the Ukalerk C-50 well, drilled in 30m water depth, gas was tested; the Kaglulik A-75, at 27m, had to be abandoned; and Nerlerk M-98, with a water depth of 52m, tested non-commercial quantities of oil.

In the Alaskan Beaufort, from the artificial gravel islands Sag Delta 3 and 4, Schio drilled two wells off the same pad and Union Oil drilled from an ice island in E. Harrison Bay.

Imperial, Gulf-Mobil and Shell-Canada Resources Ltd. were each drilling wildcat wells in the Mackenzie Delta in 1977. Panarctic's well, Hecla C-58, off of Melville Island discovered gas in 1977 but the company's offshore well near northeast Drake Pt. was dry.

An ice island prototype for drilling in Arctic waters was constructed in 1978 north of Prudhoe Bay in 3m of water by Exxon, Mobil, Phillips and Sohio. The island measured 365m in diameter and deteriorated before the end of the 1978 summer. On an artificial island near Duck Island in the Alaskan Beaufort, Exxon tested hydrocarbons.

Offshore discovery wells near Melville Island, Panarctic's Drake F-76 and Roche Pt. O-43, both tested gas in 1978 at well depths of 1128m and 2743m, respectively. Elsewhere in the Arctic seas, Dome and its various partners were drilling in the Beaufort at Ukalerk 2C-50, which was drilled to 4953 m., tested gas and abandoned in 1979. The Dome Pacific group drilled to 3250 m. at its Natsek E-56 well and suspended it in 1979. Dome's Kaglulik M-64, drilled to 144 m, was likewise suspended in 1979. And, Dome Gulf's Tarsuit A-25, drilled to 1351m, partially tested but was also suspended in 1979.

Drilling seasons from floating drillships in Arctic waters are limited to summer and early fall (from approximately late June to early October). Companies' operations on one well have often required, as a result, four or more years from initial drilling to discovery and/or abandonment. As one example, Dome's drilling in the Beaufort from 1976-79 at 13 sites resulted in three discoveries, noted earlier, at Nektoralik K-59 (oil and gas), Kopanoar M-13 (oil and gas) and Ukalerk C-50 (gas).

Those wells in the Beaufort begun and suspended in 1979 by Dome were: Kenalooak N-94, drilled to 2150 m, Koakoak O-22, drilled to 210 m. and Kopanoar 2L-34, drilled to 181 m. Drilling resumed at the Koakoak O-22 site where in 1981 Dome-Hunt-Gulf sought an oil discovery.

In 1979, Dome achieved its longest offshore drilling season to date: 150 days. Panarctic's offshore activity in 1979 was centered on three wells: Whitefish H-63, off Lougheed Island, drilled from pads of thickened sea ice, a potentially large gas field; Desbarats B-73, which was abandoned; and Hazen F-54, also abandoned.

In the Alaskan Arctic Conoco drilled at Milne Pt., to 3102 m, testing oil. In 1979, Sohio constructed its second artificial gravel island in the U.S. Beaufort, Niakuk 3, in 3.5 m. of water.

In the 1980s Sohio built its first artificial islands designed to last three years in Prudhoe Bay: Endeavour and Resolution, for wellsites Sag Delta 7 and Sag Delta 8 respectively. The Sag Delta 7 well struck oil--potentially commercial--in 1981. Off the northern slope of Alaska in the Beaufort, Esso's wells on Duck Island both tested hydrocarbons in 1980.

In 1980, Panarctic's offshore well sites were: Whitefish 2H-63, in 260 m. of water, and it produced gas; Char G-07, in water depth of 262 m., indicated gas and some oil; and Balaena D-58, in 237 m. of water, showing gas and oil. The Char G-07 well was drilled from a pad of thickened sea ice. Its Whitefish H-63 well was production tested and flowed natural gas at rates up to 1.25 million cubic foot meters per day.

Esso Resources Canada Ltd. spudded its X4 ice island well in the Mackenzie River and tested oil at a wildcat drilled on the Issungnak 2-O-61

artificial island in the Beaufort in 1980.

From drillships, Dome (and its partners) drilled at seven offshore wells in the Beaufort Sea in 1980: Killannak A-77, drilled to 702 m. and suspended until 1981; Tarsuit A-25, production tested for gas and oil, to be evaluated further in 1981-82: Koakoak O-22, drilled to 3718 m. and suspended until 1981; Kopoanoar I-44, drilled to 200 m. encountered problems and was abandoned; Kopanoar 21-44, a step-out well, drilled to 2610 m., spudded and suspended until 1981; Kenalooak J-94, drilled to 3475 m., was suspended until 1981; Orvilruk O-03, was spudded and suspended after drilling to 3606 m. until 1981.

Dome-Gulf resumed construction on the first caisson-retained artificial island in water 30 m. depth at Tarsuit N-44 in the summer of 1981, and was, at last report, to begin drilling on it in November. Oil production could start on it in 1988. Dome also continued its drilling at its earlier Beaufort wells and began testing at five new wells in the area.

Gulf-Canada Resources, Inc. was also involved in drilling at N. Issungnak L-86 from a drillship in the summer of 1981 and participated in drilling on a second well on Issungnak.

From a drillship at Issungnak 2-0-61, Esso recovered oil and/or natural gas in August, 1981 but needed more information before correctly assessing its find. In February, 1982, Esso was planning to drill from a new artificial island, Alerk, constructed of dredged materials.

In the Canadian Arctic Islands oil was discovered offshore for the first time in 1981. Up to then, only gas reserves had been tested offshore at the more than 130 wells drilled in these islands since 1961. Panarctic, drilling from platforms of artificially strengthened sea ice at CISCO B-66, off Lougheed Island, tested potentially major oil at more than 1250 m. At two other wells off Lougheed Island, Skate B-80 and MacLean I-20, the company also tested oil from artificially developed ocean ice pads.

In the Alaskan Beaufort, Sohio struck oil in 1981 from its artificial island, Endeavour, and planned two more wells in the area in 1982. Besides its two wells near Duck Island in the Alaskan Beaufort, Exxon completed another artificial gravel island, Beechey Point, in 5.5 m. of water on which it plans to begin drilling in the winter of 1981-82.

The foregoing summary is an indication of the growth level in activity in Arctic oil and gas exploration. At present, there is no producing field in the Arctic Ocean. Prudhoe Bay, bounding the Beaufort Sea, is a land-based field.

It is evident that exploratory drilling in the Arctic Ocean is being conducted from a variety of platforms: artificial gravel islands, drillships, man-made ice islands, grounded natural ice islands and artificially thickened sea ice. In terms of ocean drilling depths Beaufort drilling is relatively modest. Ice Island drilling is being conducted in about 3 m. depth, artificial gravel islands in 5 to upwards of 19 m. depth and drillships in waters of 230 and 262 m. depth.

There is some degree of uncertainty regarding the future pace of Arctic exploration, and a greater measure of uncertainty regarding the time when large-scale production of oil and gas will be forthcoming. Most operators envision production by the late 1980s and, perhaps, by the end of the decade. However, recent events, in the form of decreasing oil prices and, in Canada, a political climate which some oil investors feel is adverse to their goals, may act as a check rein to attaining full production by 1990. Technologically, the problems appear surmountable, but an adverse economic and political climate can be far more formidable than the Arctic itself.

3.0 PIPELINES AND PRODUCTION PLATFORMS

The preceeding chapter noted that there are no offshore oil or gas production facilities now operating in the Arctic. Nor, as far as can be determined, are there any such facilities under construction. There are, nonetheless, a wide variety of designs advanced for such facilities upon which the potential for conducting underwater non-destruction examination can be assessed. This chapter, therefore, deals primarily with concepts rather than existing structures. In some instances several of the platforms which are now being used for exploratory and developmental drilling are prime candidates for subsequent use as production platforms (e.g., gravel islands, caisson-retained islands, ice islands). In such instances evaluation for potential underwater NDE compatibility is on a firmer foundation.

Concurrent with this discussion of production platform types is a discussion of the present conceptualizing regarding risers, loading terminals and pipelines which also constitute an integral part of the underwater structural array coincident with Arctic oil and gas production.

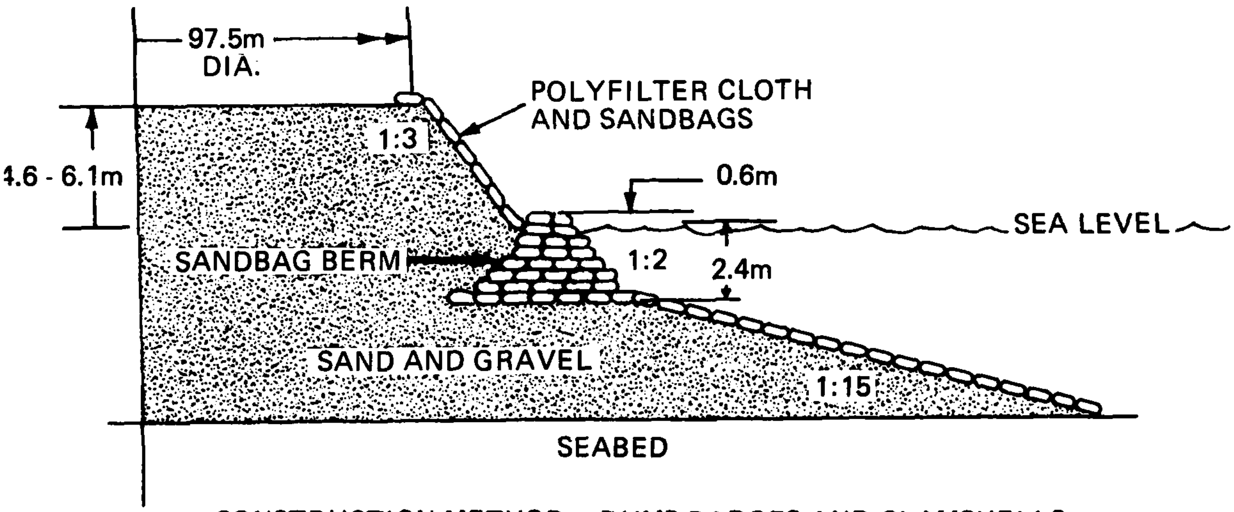
3.1 FIXED PLATFORMS

The distinction made between "fixed" and "mobile" platforms is an arbitrary one and is used simply to discriminate between those platforms which are fabricated in situ and those which are fabricated elsewhere and subsequently transported to the Arctic.

3.1.1 Artificial Gravel Islands

Since several Arctic offshore wells have been drilled from naturally-formed gravel and sand islands, the term "artificial" is used to distinguish one that is man-made vs one that is formed through natural processes. Technically, the term gravel is somewhat in error since the material size used to form the island is also sand and silt. Earth Fill Island would be more accurate, but "gravel" is in popular usage.

Canadians have been building earth fill islands for the past ten years. At present there are 18 or more such islands in the Mackenzie River Delta area of the Beaufort Sea. The materials for the islands may be dredged from around the island site or inshore. The mode of fill can be a dredge, dump barge or truck or combinations thereof. As mentioned, gravel sand or silt may be used. Silt is relatively inexpensive, but has only been used on two occasions in shallow water where a gravel ring is filled with silt and the entire mass freezes in place. In water depths exceeding about 7 m. the material is dredged up and pumped to the island site where it settles at a natural slope of 1 in 12 to 1 in 20. In less than 7 m. of water the fill may be retained by a beam of sandbags (Fig. 4) which reduces the volume of fill required. This is advantageous when fill material is scarce and must be transported to the island site from a remote source. In one instance Sun Oil, to conserve on fill, sank a barge in 2 m of water and surrounded it with silt and sandbags. Construction is normally carried out during the summer; however, three islands have been built in winter. After the ice had been cut and removed, a truck was used to transport fill from an onshore stockpile, across the ice and then



CONSTRUCTION METHOD: DUMP-BARGES AND CLAMSHELLS

EXAMPLES:	WATER DEPTH
NETSERK	4.6m
NETSERK NORTH	7.0m
KUGNALLIT	5.2m

Fig. 4. Typical sandbag retained island 2.4m water depth. (Cox, 1978)

dumped into the hole. (Offshore Engineer, Aug. 1981)

The volume of fill used to date varies widely. The least amount was 27,522 cu. m. (in 1 m. water depth) to 4,099,388 cu. m. at the deepest water depth of 19 m. water. Freeboard on these islands ranges from less than 1 m. to slightly less than 7 m. The surface area varies widely but averages about 8,027 sq. m. with a range from 5,367 to 12,922 sq. m. According to Jahns (1980), such islands offer the distinct advantage that drilling can be conducted in essentially the same manner as on land and, if initially made for exploratory drilling, they can conveniently be enlarged and transformed into permanent production platforms if discovery is made.

3.1.2 Caisson-Retained Islands

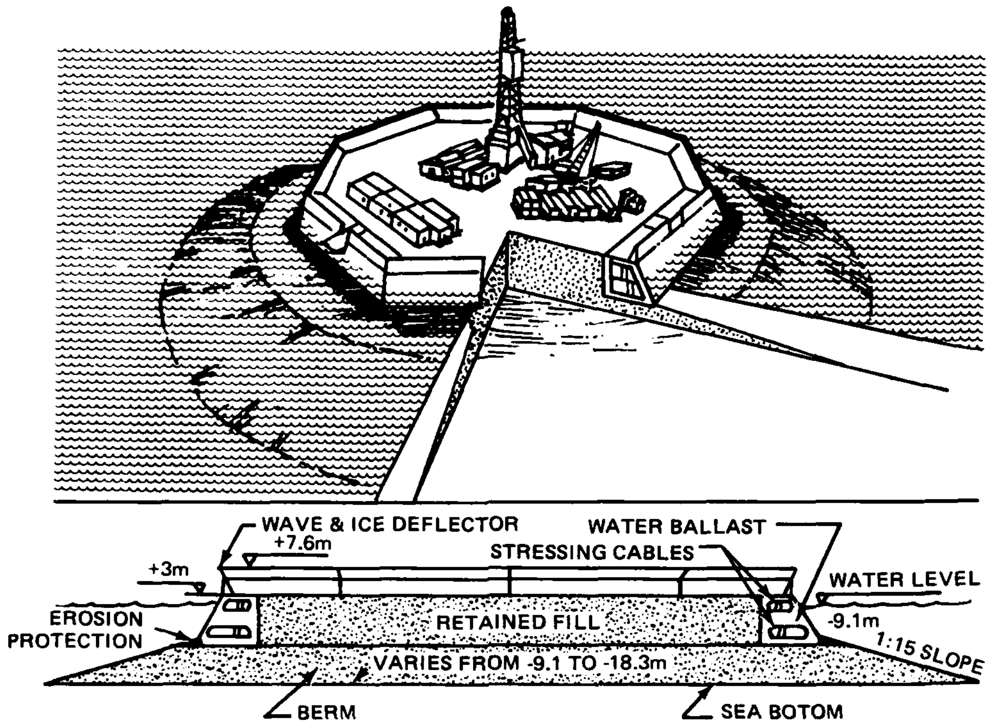
As exploration moves to deeper water and to areas where sand or gravel is not readily available, simple dredge fill islands become very expensive. The Caisson Retained Island concept of deJong and Bruce (1978) was developed to reduce costs by reducing fill requirements, simplifying construction methods and eliminating the need for elaborate slope protection.

The structure designed for this purpose (Fig.5) would consist of eight interlinked caissons proving a plan dimension, when in place, of 91.4 m across the flats of the octagon. The individual caissons are 12.2 m high with a 13.1 m base and an average length of 43.3 m. The structural design of the caissons is similar to that of icebreakers, in that they are held in a ring by stressing cables. The stressing system is made continuous by means of couplers at each end of each caisson. The caissons will be towed to location as a ring and set down on a previously prepared berm built up to 9.1 m below mean sea level. The center of the ring will then be filled with sand providing the base for the drilling equipment. It is the intention to raise and transfer the caisson ring to a new location each summer. This set of caissons was primarily designed for the Mackenzie Delta area of the Beaufort Sea. However, the concept can be used on other Arctic shelves, provided the design criteria are adapted to local conditions.

Similar to the unretained gravel island, drilling operations on the retained island are conducted as they would be on a shore-based site. Although the designers (deJong and Bruce, ibid.) do not specifically address the question, it is assumed that the caisson-retained island can be converted into a permanent production platform. Lee (Offshore Engineer, Aug. 1981), remarking on caisson-retained islands in general, estimates that such islands would be satisfactory as a production platform in as much as 30 m. water depth.

3.1.3 Ice Islands

Several Arctic offshore drilling companies have used grounded ice islands and artificially constructed ice islands (Fig.5) for exploratory drilling. While most of these islands seriously deteriorated during the summer months and forced curtailment of drilling, there is, based on the several years use of T3 (Fletcher) Island, evidence that such ice islands might serve as production platforms in shallow water if ice is added to make up for summer losses.



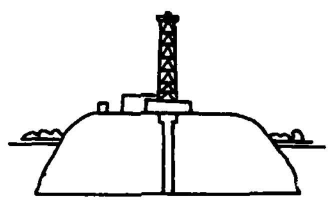


Fig. 5. Top: Caisson retained island (from deJong and Bruce, 1978)

Bottom: Ice island

During the winter of 1976-1977, Union Oil drilled an exploration well from a grounded ice island built in 2.7 m. of water in Harrison Bay, about 80 km. west of Prudhoe Bay (Kry, 1977). Construction of the Union ice island began in early November by repeated flooding of the ice surface with seawater. The ice was gradually thickened and eventually grounded to form a platform for the drilling operation. Island construction was completed by 20 January when the platform had a freeboard of about 1 m. The drilling rig was moved on and the well drilled in time to vacate the island by mid-April. The ice island melted and disappeared in early July.

Unlike gravel islands, ice islands lack stability owing to their low weight and need to be protected against lateral movement of the surrounding ice. The Union ice island was protected by the maintaining of a 3.3 m. wide moat around the majority of the island. The moat therefore separated the island from surrounding ice that might push it off station.

According to H.O. Jahn (1979), Exxon, in cooperation with three other companies (Mobil, Phillips and Sohio), has conducted a prototype experiment to extend ice island technology. During the winter of 1978/79 a large experimental ice island was constructed in 3 m. of water north of Prudhoe Bay. A modified center-pivot irrigation system was used during part of the experiment. The diameter of the island was about 366 m. and it achieved more than 6.1 m. freeboard at the center. The experiment had the following objectives:

1. To test improved techniques for rapid, streamlined ice island construction.

2. To demonstrate the concept of a large ice island with sufficient mass to resist lateral ice forces during spring breakup.

3. To observe the rate of deterioration of a large ice island during the summer open-water season.

The experiment accomplished all three objectives. A massive island was constructed that remained on location through breakup. Deterioration during the summer was found to be significant, and the island disappeared before the end of summer. This means that some sort of melt protection is required if the ice island is to be available for a second winter drilling season. The feasibility of preserving an ice island through the open-water summer season has not been demonstrated. In any case, Jahn (ibid.) concluded, the need for protective measures would add to the cost and reduce the economic attractiveness of two-year ice island concepts.

3.1.4 Offshore Tunneling and Chamber System (OTACS)

This concept was formulated by Lewis et al (1977) to take advantage of:utilizing onshore drilling equipment, reduced drill mud hydrostatic pressure, absence of weather-related effects, large oil storage capacity availability and oil spill control.

The concept envisions a 16 km long tunnel with eight drilling chambers (Fig. 6) 2 km. apart for a reservoir of 48 km^2. Twelve wells per chamber are proposed which would accommodate 96 wells, presumably adequate for field development. The two tunnels (one for drilling supplies; one for fresh air and emergency exit) would be at a depth of 600 m.

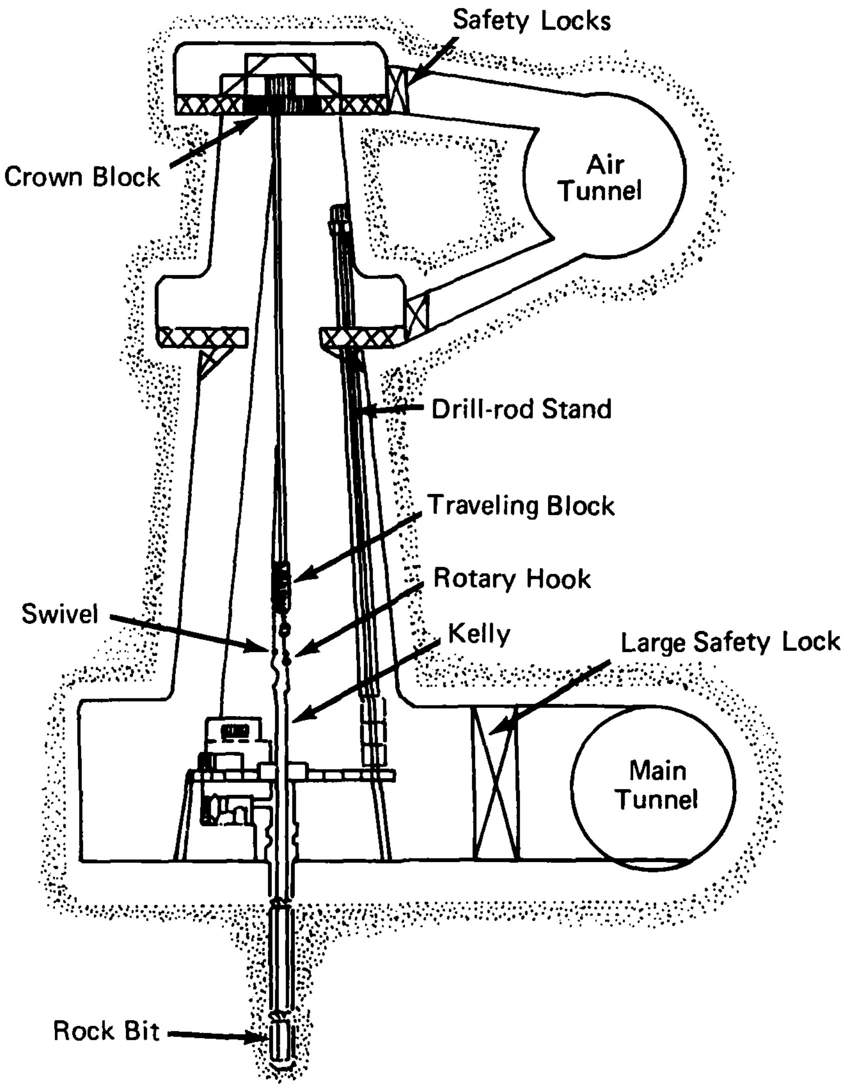


Fig. 6. Drilling chamber in a tunnel concept. (Lewis et al., 1977)

With regards to NDE, this concept, if adopted, would permit conventional land-based or surface techniques.

3.2 MOBILE PLATFORMS

3.2.1 Barges

Although designed as a drilling platform, The Offshore Company's drill barge (Fig. 7) offers the potential to serve as a production platform as well. The barge is designed to operate year-round in the nearshore in water depths of 2 m. to 9 m. which characterize the water depths inside the Barrier Islands of the Beaufort Sea.

The steel-hulled barge acts as a submersible and rests on the seafloor. Two large columns support the superstructure. One of the columns contains a moonpool for drilling and the other provides elevator access to the hull.

A unique split stack BOP system allows the barge to separate from the well in emergency conditions. The subsea BOP array is recessed in a caisson below the mud line.

The hull sides are sloped at a 45-degree angle, reducing ice loads by a factor of 10. Ice rides up the slope and breaks over the top of the hull as a result of its own weight. The ice is prevented from freezing to the hull by a system which directs heated water through channels along the interior side of the hull plating.

The superstructure and the hull are separated by a 6 m. air gap. The two 7.9 m. diameter columns are ice-strengthened to allow continued operations without active ice handling measures. The superstructure, measuring 59 m. by 29 m. has its longitudinal axis perpendicular to the longitudinal axis of the hull.

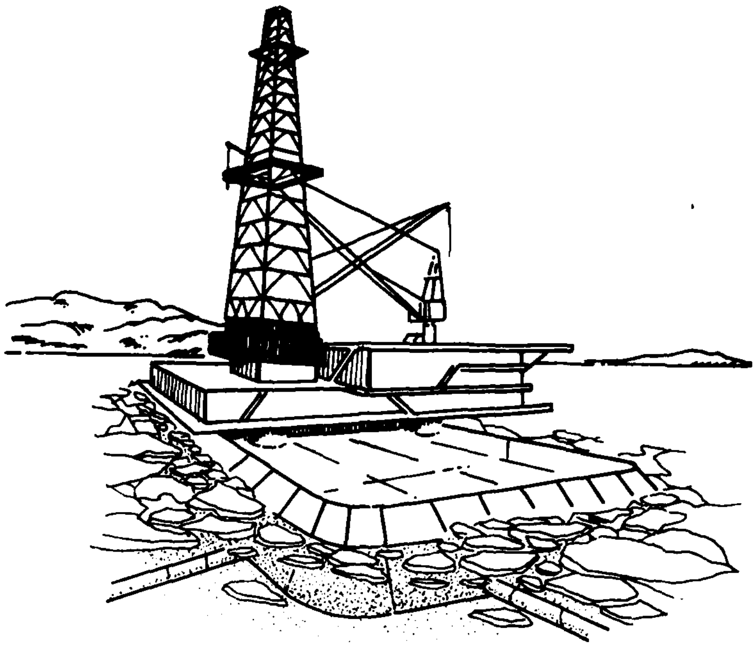
3.2.2 Monopod

Experience with design approaches in Cook Inlet served as a model for the Arctic Ocean which led to the Monopod. Subsequent field tests to measure directly the crushing strength of ice in Mackenzie Bay formed the basis for the design of a monopod structure for exploratory drilling which received "Approval in Principal" by the Canadian Government (Jazrawi and Davies, 1975, in Jahn, 1980). The structure was intended for use in water depth from 3 m. to 12 m. and, with a column diameter of 9.1 m., it is designed for ice loads in excess of 9,072,000 kg. More than twice the design load of the typical four-legged Cook Inlet structure. This structure, according to Jahn (ibid.), was never built since artificial islands were economically and technically more attractive.

3.2.3 Cone and Monocone

Several companies (Chevron, Esso Resources Canada, Imperial Oil) have investigated cone and monocone structures in terms of mobile drilling platforms which also offer the potential for later serving as production platforms.

The cone or fixed cone structure shown in Figure 7 is a design by The Offshore Company later adopted by Chevron and designated the Arctic Mobile Drilling Structure (Offshore, May 1980). The structure is composed of steel



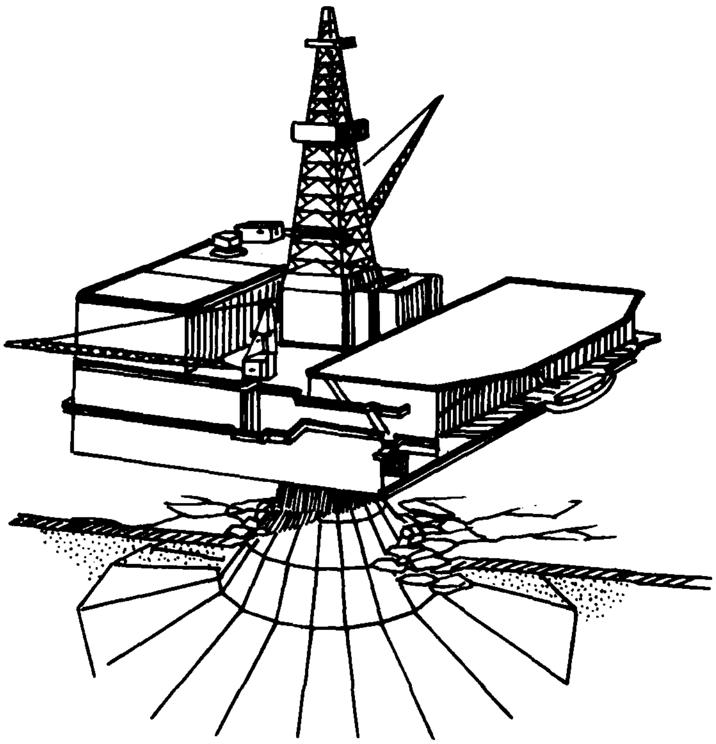


Fig. 7. Top: The Offshore Company's Artic Drill Barge (from Offshore, May 1980)

Bottom: Chevron's Cone Structure

and is designed for year-round operations in the nearshore environment of 5 m. to 20 m. water depth, larger design concepts permit operations in water depths up to 60 m. The structure utilizes a gravity foundation using seawater to ballast the lower hull sections for vertical mass. Relocation, if required, is accomplished by de-ballasting the vessel, towing it to a new site, and re-ballasting. The hull at the water line employs an inverted cone surface to uplift and shear the ice sheet. The surface of the lower cone is heated by a hot water system and the upper cone is heated by electrical resistance heaters. The structure incorporates a shallow skirt system at the base. A passive suction relief system is provided to eliminate high skirt cavity over-pressures during set-down and suction pressures during refloating. In order to position the hull in all but minimum water depths, the unit must be rotated by shifting the ballast until one edge of the hull touches bottom. Then the remainder of the ballast tanks can be flooded. The unit will heel over 14 degrees at touchdown in 18 m. water depths. For refloating the procedure is reversed.

Another cone design, similar in theory but somewhat different in configuration, was conceived by Esso Resources Canada for water depths up to 40 m. ERC's structure envisions utilizing concrete instead of steel.

The monocone structure (Fig. 8) was designed to mitigate the cone's major weakness which required that it be in a certain position, relative to water level, to minimize ice loads. A movable conical collar is used which can be adjusted in the vertical on a cylindrical shaft to an optimum ice-breaking position. According to Jahn (op. cit.), monocone structures have been designed for three water depth ranges: 11 m to 21 m; 21 m to 41 m and 41 m to 61 m. Their advantages over fixed cone structures with similar depth ranges are reduced weight and reduced cone surface area where heating or special coatings are required to prevent ice freezing to the structure.

3.2.4 Floating Caisson

Proposed by B.C. Gerwick, University of California and H.O. Jahns, Esso Production Research, the floating caisson (Fig. 8) is aimed more toward the future rather than the present.

The unit is made of concrete and was designed for the relatively deep waters of the subarctic environment with possible application to year-round ice pack operation. The subarctic version of the caisson has an hourglass configuration at the waterline to break the ice sheet either in a downward or upward mode. The Arctic version has only an inclined angle to break ice downward, because the failed ice is easier to move past the structure below the ice sheet rather than above.

The breaking of the ice sheet is accomplished with an induced heave motion of the caisson. Subarctic model test applications indicate the structure can operate in moving pack ice up to 2.4 m. thick with 14 m. ridges. The caisson's mass, about 362,880 tonnes, and size can be increased to withstand multiyear floes and heavier ice sheet conditions.

The caisson is designed to work in water depths ranging from 305 m. to 975 m. Mooring lines are run through fairleads at the base of the

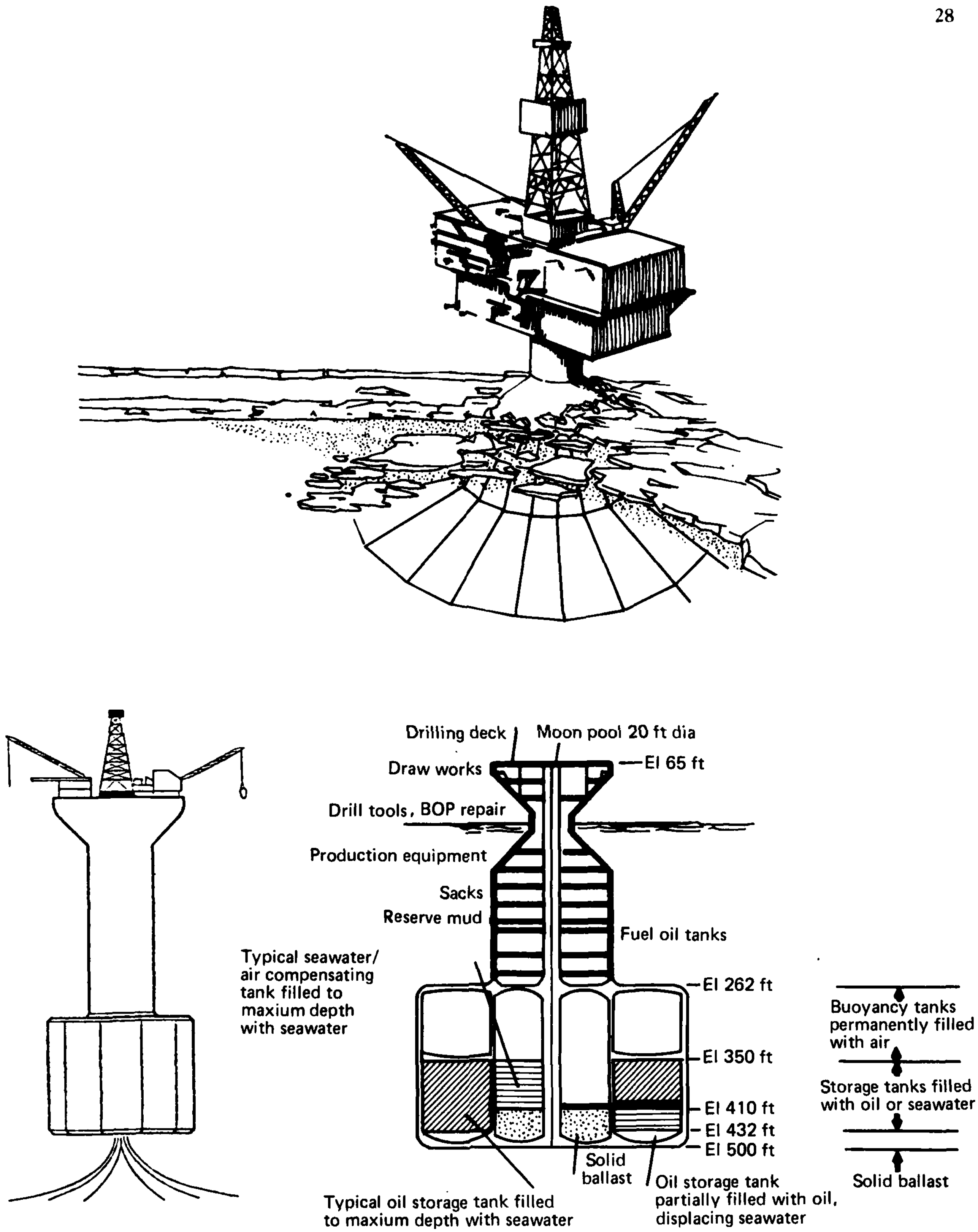


Fig. 8. Top: Esso Resources Canada's monocone structure.

Bottom: Floating Caisson. (from Offshore, May 1980)

structure. Heave is induced by a periodic pull-down on the mooring lines using an intermittent stroking machine, or by periodically releasing compressed air in the ballast.

3.2.5 Subsea Completion Systems

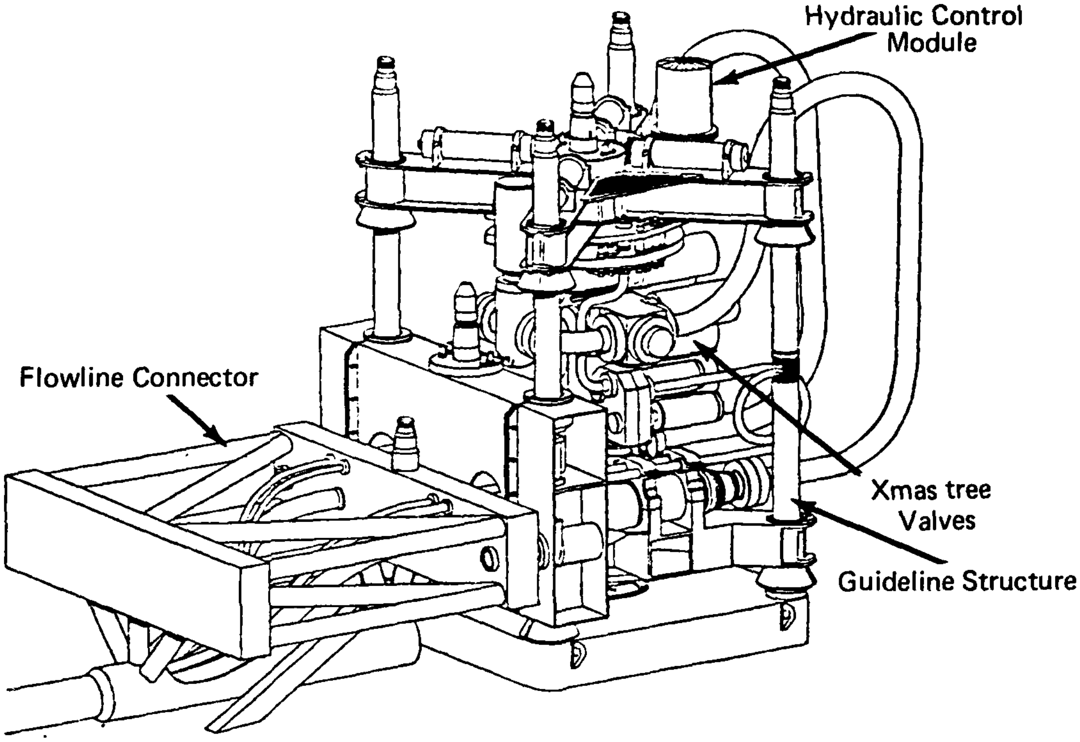
Subsea Completion Systems have been defined as the completion of a producing well in which the producing christmas tree and all other primary well controls, either exposed to the water or fully encapsulated (wet and dry systems, respectively), are located on the sea floor (Offshore, Aug. 1975). They are serviced and maintained by divers, remotely operated vehicles or by manned submersibles.

There are over 272 (wet and dry) subsea production systems in place on the sea floor. In 1978 Panarctic Oils, Ltd. installed a wet, single 13.97 cm (5.5 in.), 351 kg/cm^2 (5,000 psi) diverless, satellite gas well with dual 15.2 cm (61 in.) flowlines in 55 m. of water. The well (Drake F-6) was installed in the Beaufort Sea, it was controlled remotely from a shorebased facility and successfully produced for seven months before shutting in. A schematic of the wellhead, manufactured by Regan Offshore International, is presented in Fig. 9. As mentioned in Chapter 1, the christmas tree is placed in a "glory hole" at a depth prescribed to preclude ice scour.

A second type of subsea completion system is the dry system such as manufactured by Can Ocean Resources, Ltd. In this type system the wellhead cellar is encapsulated within a dry, 1-atmosphere chamber wherein installation/maintenance work is conducted in a shirtsleeve environment. A schematic of a dry wellhead cellar is shown in Fig. 9. For multi-well operations a sea bottom, 1-atmosphere manifolding center is provided. Transportation of personnel to and from the chambers is provided by a 1-atmosphere transfer capsule which is launched and retrieved from a surface ship. All breathing gasses, power, communications, etc., are provided through a unitized umbilical from the surface to the transfer capsule which docks and mates to the wellhead or manifold center. There are, at present, no such systems working in the Arctic, although there are three complete multi-well systems produced by Can Ocean working elsewhere in the world.

A third system, the Neutrabaric System, designed by Vickers-Intertek, reflects aspects of both the wet and dry system. The Neutrabaric system is defined (Ball, 1977) as a combination of water-filled, subsea-located pressure vessels containing equipment to which man access is required; within which the pressure may be reduced to a nominal 1-atmosphere absolute pressure by mating on a dry, 1-atmosphere,absolute--pressure, air-filled personnel transport unit and using its reference pressure to effect the neutrabaric depressurization. Personnel may then enter and work in the nominal 1-atmosphere absolute pressure, water-filled chamber in swimming pool conditions free from decompression problems.

The system (Fig. 10) encapsulates the christmas tree within a spherical chamber some 3 m. diameter and then floods the chamber with sea water at ambient pressure. A second water-filled chamber is required to house control and auxilliary equipment and is interconnected to the first chamber. A third chamber, or a submersible, which is dry and at 1-atmosphere can mate to the control chamber and is used to carry personnel from and to the surface. To date, operational employment of the system has not been reported, although an operational prototype has been constructed.



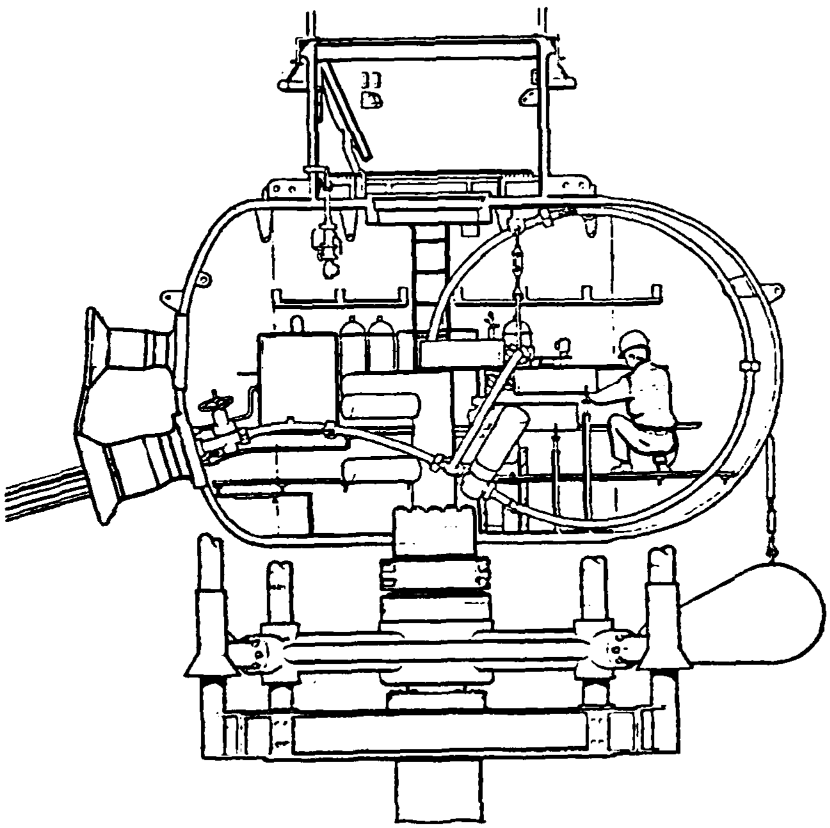


Fig. 9. Top: Pan Arctic's gas tree with flowline bundle landed and locked. (Offshore Services, Jan., 1978)

Bottom: CanOcean Resource's 1-atmosphere dry wellhead cellar. (World Oil, Jan., 1977)

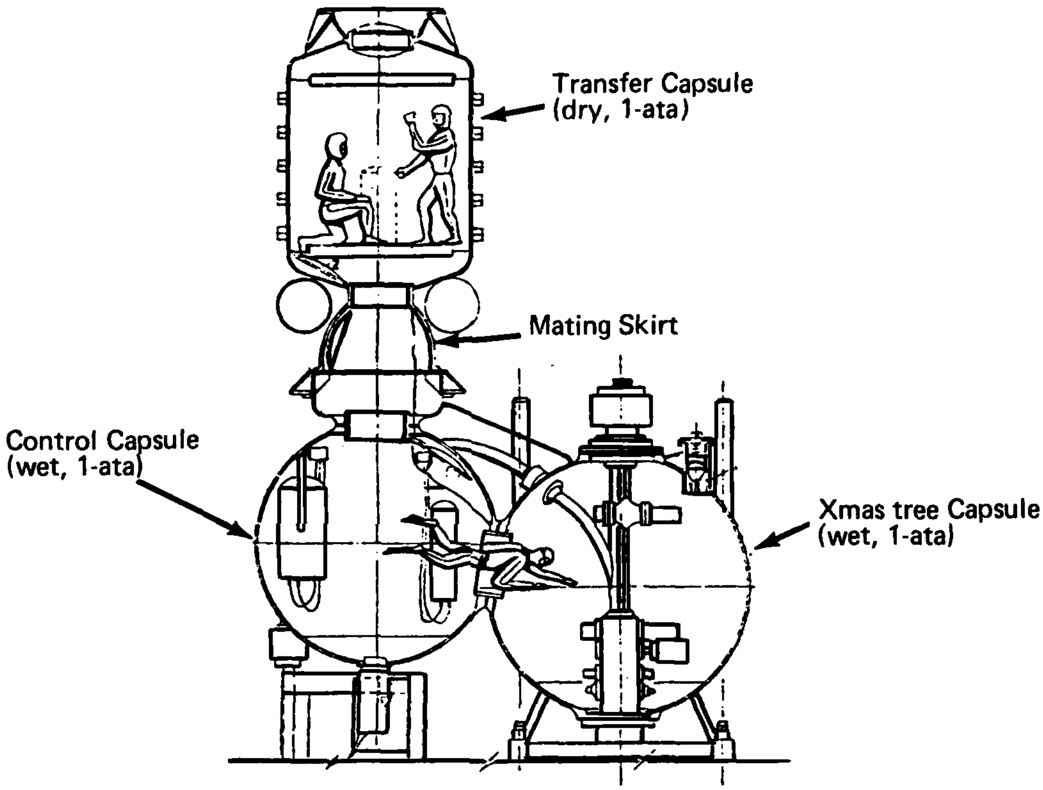


Fig 10. Vickers-Intertek Neutrabaric System (from Ball, 1977)

3.3 PRODUCTION RISERS

In many aspects several of the problems associated with risers in ice-free ocean areas will not be present in the Arctic. All of the conceptual designs for production platforms presented in the foregoing sections envision enclosing the riser in the leg of the platform or within the gravel-filled or ice island. Under these conditions the riser will be protected from ramming by ships, crushing by ice and, since there is no sunlight or moving water in the vicinity of the riser, fouling will be minimal to non-existent. From an underwater NDE point of view riser inspection, at least externally, should be able to be conducted under optimum conditions.

3.4 OIL AND GAS LOADING TERMINALS

Very little is available concerning the prospective design, materials or configuration of candidate oil and gas loading terminals in the Arctic. G. E. Mott, Manager, Central Offshore Engineering of Texaco presented the following observations in April 1981 at a Battelle Memorial Institute workshop regarding Arctic loading terminals.

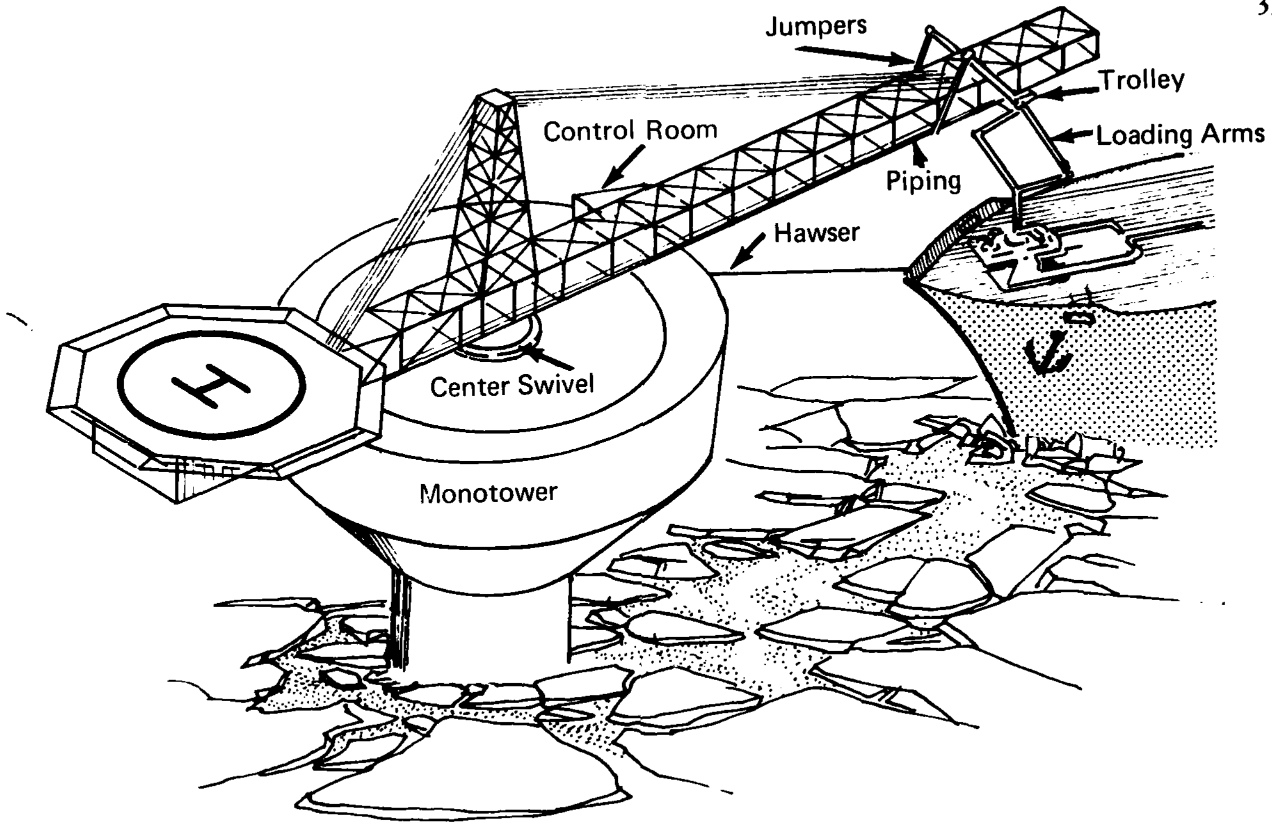
New types of oil and gas loading terminals will be required for use in the Arctic. Several concepts have been proposed. But none has presently been built or tested in a severe ice environment. In areas where ice is not a year-round problem and where normal annual sea ice is not over 1.5 to 2 m thick, it appears that several types of terminals may be utilized. Among these are fixed single point mooring towers, oscillating columns or towers specially adapted for ice areas by adding a catenary mooring system to transmit ice loads from the column to the sea floor by anchor lines, and Single Anchor Leg Moorings (SALM's) or oscillating columns which do not protrude over the surface of the water or can be submerged by the ice or by ballasting to avoid a design to withstand the severe ice loads. It appears that these terminal structures can be designed and built for up to about 300 m of water in areas subject to moderate sheet ice at present.

One Arctic offshore loading terminal concept is shown in Fig. 11 where risers from the submarine loading lines carry oil to the loading arms. The loading arms are fitted with a quick disconnect, which mates with a companion fitting on the tanker bow. The loading arms and hoses are insulated and trace heated to protect the contents from freezing or becoming too viscous to pump.

3.5 PIPELINES

There is some indecision at present concerning the role undersea pipelines will play in the Arctic. In the Beaufort Sea area pipelines seem to be a foregone conclusion owing to the presence of the Trans-Alaskan Pipeline System. The rest of the Arctic and the sub-Arctic will likely have tanker transportation, although in the Bering Strait it is still uncertain that tankers will be able to operate routinely. The MANHATTAN VOYAGE in 1969 demonstrated that an east-west transit through the Northwest Passage could be accomplished by a commercial vessel, but it has not yet been shown that this can be performed on an economic and regular basis. (Offshore Engineer, Aug. 1981)

Undersea pipeline installation and protection feasibility studies have been conducted for some number of years. One such program has been the



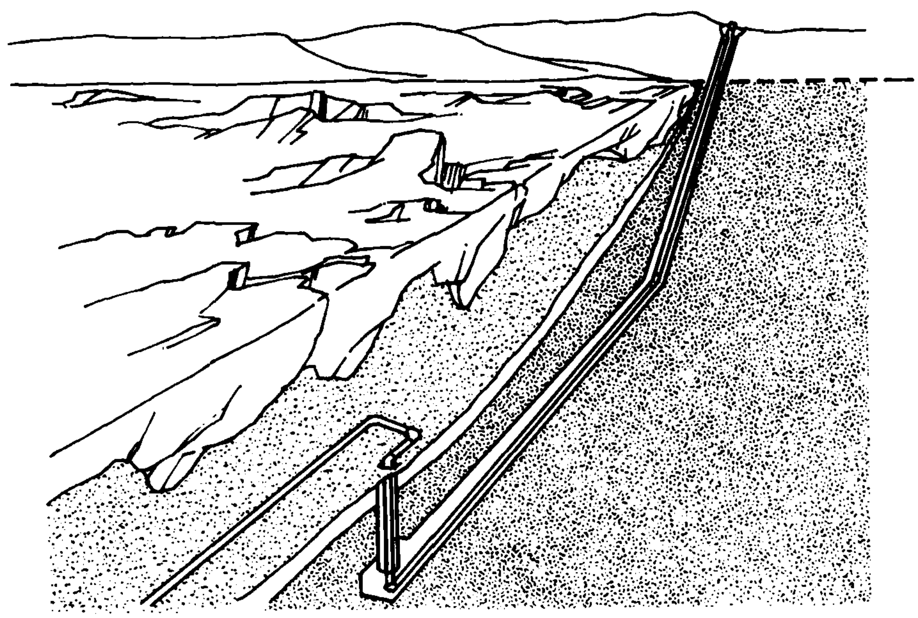


Fig 11. Top: Loading Crane Concept (from National Petroleum Council, 1981)

Bottom: The Polar Gas Project Concept for pipeline strait crossing installations. (from Noroil, May 1981)

Polar Gas Project which began in 1972 to determine the best means of transporting the naturalgas discovered in the Canadian Arctic to southern markets. (Sponsors of this project are TransCanada Pipelines, Tenneco Oil of Canada, Ltd., Panarctic Oils Ltd., Ontario Energy Corporation and PetroCanada.) As one part of this project techniques have been developed to install and connect sections of 91cm (35 in.) diameter pipe underice in 500 m. of water.

There are several conceptual approaches toward installing and protecting pipelines underice, and the final outcome will have significant impact on the type of NDE which can be performed. Two of the major problems, ice scour and pipe temperature, are particularly important since the solutions to those problems will determine the extent to which present NDE equipment can be employed.

To protect the pipeline from ice scour two methods are advanced: burial and tunneling. Burial may be accomplished by jetting, plowing or dredging. Since protection from ice scouring may require burial from 6 m to 7.5 m. depth, dredging appears to be the most likely solution to burial, providing techniques can be developed to dredge to this depth in up to 45 m. water depth. To partially alleviate the depth of burial problem, backfilling with an ice-resistant berm is being considered. Tunneling o the pipeline is the preferred method for protection of the shore approach in the Polar Gas project. The pipeline, at 45 m. depth, would then be connected by a riser to that section of the pipeline beyond this depth (Fig. 11). In six of the marine crossings the Polar Gas pipeline would traverse,bringing gas from Ellef Rignes Island, the northernmost of the Arctic islands, to the southern coast of Melville Island, there are two straits, Pullen and Crozier Strait West, when the entire crossing of 4.2 km and 3.3 km, respectively, would be performed by tunneling.

Insulation of the pipeline will influence the type of external NDE which can be performed since the pipe itself will not be visible and certain types of examination which require making direct physical contact with the pipe or its anti-corrosive system may not be possible.

4.0 INSPECTION REQUIREMENTS

Requirements for inspection of undersea structures emanate from two main sources: Federal/State Governmental bodies and the platform operators. A third group, various classifying societies such as the American Bureau of Shipping, Det Norske Veritas, Lloyds Register of Shipping, etc., set up inspection standards based on the requirements of federal governments, operators and assurers of platforms. The societies, it should be emphasized, are not in themselves requirements originators; they develop standards. In the same category are other professional societies such as the American Welding Society, the American Society of Mechanical Engineers and the American Society of Nondestructive Testing who produce code standards of their respective societies.

A comprehensive survey of the above sources regarding their inspection requirements was made in 1978 and published in Underwater Inspection/Testing/Monitoring of Offshore Structures (Busby Associates, 1978). This report is recommended for a detailed review of the various governments/responsibilities regarding undersea structure inspection and the self-imposed inspection requirements the operators of producing structures have placed upon themselves. The following is a summation of the inspection requirements, as promulgated and envisioned by the countries bounding the Arctic Ocean (excluding the Soviet Union) and by offshore oil operators in the Canadian and U.S. Arctic.

4.1 U.S. Governmental

4.1.1 Federal

The National Research Council's Marine Board capsulized U.S. Federal Government's role in undersea inspection in the report Inspection of Offshore Oil and Gas Platforms and Risers (1979), the following is an excerpt from that report.

The safety of oil and gas operations on the Outer Continental Shelf is a primary responsibility of the Department of the Interior (DOI). In its publication "Policies, Practices and Responsibilities for Safety and Environmental Protection in Oil and Gas Operations on the Outer Continental Shelf," (1977) the USGS has described its responsibilities, which are mandated by the U.S. Congress in the OCS Lands Act of 1953 (43 USC 1331-1343) as amended. Accordingly, the USGS is required to:

- Protect against losses to human life and property, injuries to personnel, damages to the environment, and waste of natural resources by means of an organized and systematic approach to the preleasing and leasing of potential or known oil and gas sites on the OCS.

- Establish requirements for safe drilling and production operations on the OCS.

- Ensure that the oil and gas industry complies with regulations, safe practices, and environmental safeguards through the development and enforcement of stringent requirements.

- Maintain an R&D capability for improving the functions it is required to do.

At present the DOI has not promulgated a formal program for undersea structure inspection. A conference was held with personnel at the Anchorage office of the Geologic Survey which revealed that they saw no immediate problems in regards to undersea inspection, but that at this time it was perhaps premature to address this question since offshore Arctic production was not imminent.

According to Mr. R. Giangerelli, Minerals Management Service, a Memorandum of Understanding (MOU) between the U.S. Coast Guard and MMS was signed on 18 December 1980. This MOU (published in the Federal Register, 8 January 1981, Vol. 46, No. 5, pp. 2199-2203), states that the MMS ". . . regulates all mineral exploration, drilling, and production activities on leased or leasable land;" whereas, the Coast Guard ". . . regulates to promote the safety of life and property on OCS facilities and vessels engaged in OCS activities, and the safety of navigation." In addition, the MOU states that the MMS ". . . . . exercises technical review and approval responsibility for design, fabrication, and installation of all fixed OCS facilities. Additionally, after technical review and approval of the design and fabrication of all floating OSC facilities by the Coast Guard the (MMS) will have final approval responsibility for the installation of such facilities." The Coast Guard, meanwhile, "exercises technical review and approval responsibility for design and construction of all floating OCS facilities, and all vessels engaged in OCS activities, including mobile drilling units and mobile well servicing units." Subsequent discussions and agreements between the MMS and the Coast Guard have defined some of the conditions in which a mobile drilling unit is considered immobilized and, therefore, becomes a fixed platform subject to MMS regulation. These discussions are held whenever a question is raised about the status or potential status of a floating or mobile OCS facility.

Since 1976 the Office of Pipeline Safety (Department of Transportation) has had responsibility for providing inspection requirements (surface and underwater) for pipelines. Under the gas pipeline safety regulations Title 49 of the Code of Federal Regulation, Parts 192 and 195, the following regulations apply to offshore pipelines:

"192.465(a) Each pipeline that is under cathodic protection must be tested at least once each calendar year, but with intervals not exceeding 15 months, to determine whether the cathodic protection meets the requirements of 192.463..."

"192.613(a) Each operator shall have a procedure for continuing surveillance of its facilities to determine and take appropriate action concerning changes in class location, failures, leakage history, corrosion, substantial changes in cathodic protection requirements, and other unusual operating and maintenance conditions."

"195.412(a) Each carrier shall, at intervals not exceeding 2 weeks, inspect the surface conditions on or adjacent to each pipeline right-of-way."

According to Mr. C. Deleon, Office of Pipeline Safety, 192.613(a) is applicable to underwater pipelines and is interpreted to mean that if evidence existed to show that a pipeline required surveillance, then a surveillance or inspection program would be required on the operator's part. Section 195.412(a) can be satisfied by air or water craft route patrols.

The Department of Labor's Occupational and Health Administration (OSHA) has transferred its work place safety responsibility on the OCS to the Coast Guard. The MOU, described above, identified this responsibility as a function of the MMS. OSHA has, however, retained work place safe responsibility within state controlled waters.

The U.S. Environmental Protection Agency (EPA) is generally responsible for pollution control and waste disposal in waters of the territorial sea, the contiguous zone, and the high seas.

The National Oceanic and Atmospheric Administration (NOAA) houses the Office of Coastal Zone Management, which administers the coastal zone programs of the states as directed by the Coastal Zone Management Act of 1972 as amended (76 USC 1451-1464).

4.1.2 State Governments

No state has underwater inspection requirements for fixed offshore structures. Two states, Texas and California, have rules and procedures which are applicable to drilling, production and pollution control, but these are directed primarily to hardware/component material and test specifications. The closest procedure regarding periodic monitoring is the California Lands Commission's: Procedures for Drilling and Production Operation from Existing Facilities, Outside and Submerged Lands Currently Under State Oil and Gas Leases. (11 December 1973). Under Section F.7.h of these procedures it is stated:

The ocean surface above all pipelines that service offshore structure, shall be inspected a minimum of once each week for indication of leakage, using aircraft or boats. Records of these inspections, including the date, methods, and results of each inspection, shall be maintained by the operator in its local district office.

Inquiries made of staff members of representatives from the State of Alaska and to the Office of the State of Alaska revealed that nothing in the way of rules or requirements for undersea inspection were being written at this time, nor were there any imminent plans to do so.

4.2 Canada

The Canadian government's Department of Energy, Mines and Resources has, as of July 1981, developed a draft of Canada Oil and Gas Pipeline Regulations which is now undergoing review by the Canadian oil industry. While those regulations are not yet a legal requirement, a review of those aspects dealing with underwater and offshore pipelines reveals the present thoughts of Canadian government officials regarding pipeline inspection. Coincidentally, regulations for structure inspection are also being developed, but these are not yet available to the general public.

As presently envisioned, the Canadian regulations encompass a sequential process which the operator is obliged to follow from pre-design to post-emplantment. The following proposed requirements are extracted from the draft regulations and only deal with those aspects of the regulations concerned with underwater pipelines and their inspection.

Approval to Construct

drawings showing:

1. the proposed location of the pipeline colored in red,

2. the regional topography of the area for a distance of 200 metres

on both sides of the pipeline on land or for a distance of 600 meters on both sides of the pipeline in the offshore area,

3. for offshore pipelines the water depth and the means in which continuous support will be provided to the pipe,

geotechnical studies including topographical maps detailing:

1. the river and lake bottom conditions where the pipeline route crosses such bodies of water, the incidence of water scouring around or beneath ice dams and the potential for bottom erosion and silting that may result from the installation of the pipeline,

2. for proposed offshore pipelines, complete hydrographic survey details including but not necessarily limited to a profile of the seabed and incidence of ice and iceberg scouring;

Prior to Construction, the holder of an Approval shall submit copies of

1. a description of the non-destructive testing procedures for field welds, including the methods and techniques to be used;

2. a description of the duties and authority of each party involved in the performance of non-destructive testing and the interpretation of test results; and

3. a description of the inspection program to be used during the purchase of materials and the construction of the pipeline.

Approval to Operate

This must be obtained and the following information must be furnished:

- a summary of the results of the non-destructive testing of field welds.

DESIGN

General Requirements

Each buried or submarine pipeline shall have an external protective coating and shall be cathodically protected in its entirety within one year following completion of construction unless otherwise approved by the Chief. (Chief Conservation Officer)

Where the condition of the ground or backfill is such that the pipe may be uplifted by its own buoyancy, measures shall be taken to maintain the elevation of the pipe relative to the ground surface.

Burial Depth

An operator shall design and install a pipeline so that the minimum cover between the top of the carrier pipe and the grade level is

one meter except that in rock the minimum cover shall be 0.6 meters and for river crossing 1.25 meters, unless otherwise approved by the Chief.

For offshore pipelines and river crossings, an operator shall coat the pipe with a material which will give the pipe the required design negative buoyancy and protection from external forces unless otherwise approved by the Chief.

For offshore pipelines, all pipeline components extending from the seafloor to the production structure shall be protected against physical damage and corrosion.

Inspection of Construction

Dents that have dimensions exceeding either six millimeters or two percent of the outside diameter of the pipe in a pipeline intended to operate at forty percent or more of the SMYS (Specified Minimum Yield Strength) of the pipe material shall be cut out as a cylinder.

Dents containing notches, gouges or other stress concentrators shall be cut out as a cylinder.

Dents located within one hundred and fifty millimeters of any pipe weld shall be cut out as a cylinder.

An operator shall non-destructively test the entire circumference of all field welds.

INSPECTION

(1) An internal inspection of the trunk lines shall be undertaken every three years unless otherwise approved by the Chief.

(2) For offshore pipelines, a visual inspection shall be carried out not more than twelve months after installation including

(a) a subsea survey of the pipeline and of the seabed of not less than 5 meters on either side of the pipeline in order to monitor the condition of the pipeline, pipeline support, and seabed in the immediate vicinity;

(b) external inspection of pipeline risers and their supports;

(c) internal inspection of the pipeline and risers;

(d) a survey of the pipework, valves, fittings and pig traps associated with the pipeline located on the production structure;

(e) tests to ensure the effectiveness of the cathodic protection system;

(f) checks on the operability of all subsea and other valves;

(g) checks on all safety and control equipment; and

(h) external inspection of all mechanical connectors.

(3) Notwithstanding subsection (1), for offshore pipelines, annual inspections shall be undertaken for risers and their supports, reinforced flexible pipelines, trunk lines, spur lines, laterals, flow line valves and fittings, unless otherwise approved by the Chief.

(4) For offshore pipelines, the areas in proximity to the pipeline shall be surveyed in order to detect the approach of icebergs, fishing activities, and marine accidents.

(5) Suitable measures shall be taken to minimize both the impact of icebergs, fishing activities and marine accidents on the pipeline and the possible resultant impact on the environment.

Cathodic Protection

(1) An operator shall undertake an annual survey each calendar year, to ascertain if its cathodically protected pipeline systems meet accepted criteria for cathodic protection.

(2) An operator shall verify the operation of the impressed current systems at intervals of not more than six weeks.

(3) An operator shall institute programs for monitoring the effect of corrosion and internal erosion on pipelines.

Annual Pipeline Report

Within one month of the end of each calendar year:

results of all inspections made during the year.

SITE RESTORATION

Upon termination of the pipeline operations

all seafloor or subsea equipment shall be removed unless otherwise approved by the Chief.

4.3 Norway

The Norwegian Petroleum Directorate is the Certifying Authority for structures in Norwegian waters. The legal basis for platform inspection is a Royal Decree of 9 July 1976 relating to safe practice for the production, etc., of submarine petroleum resources. In practice, the Petroleum Directorate employs the classification society Det Norske Veritas to carry out certification work and surveys on its behalf.

A draft of Provisional Guidelines for the Inspection of Structural Parts on Production and Shipment of Installations and Pipeline Systems was issued by the Petroleum Directorate on 2 April 1977. Although the Petroleum Directorate's

Guidelines are provisional, they are none-the-less an official opinion of the Norwegian Government and, since National regulations and rules take precedence over classification society rules, it is appropriate to review these regulations regardless of subsequent modifications.

Steel Structures (Underwater)

Initial inspection shall normally comprise:

a) Visual inspection of the structure to locate mechanical damages, possible metallic waste in contact with or in the immediate vicinity of the structure.

b) Visual inspection of type, length and quantity of marine growth on areas pointed out beforehand in different depth levels (photo documentation).

c) Localization of corroded areas (photo documentation).

d) Visual inspection of the anode condition. The inspection shall comprise a sufficient representative number of the total number of anodes. The inspection shall also comprise potential reading of selected anodes.

e) Visual inspection of the sea bed for possible erosion or building up of scour (photo documentation).

f) MPI-inspection of selected nodes (selected in the design phase).

Annual inspection

Annual periodic inspection shall be based on the results from previous inspections and shall, in addition to the items mentioned above (a-f) also comprise:

Implementation of NDT-thickness-measurements on selected spots for reference measurement. In addition, the measurements shall comprise areas which, based on previous inspection and experience, have revealed these as relevant for thickness control purposes. In this connection due consideration shall be taken to areas having been revealed by potential readings to be corroded areas, special stress and/or fatigue areas.

Photo documentation shall at least comprise the same areas as specified for the initial inspection.

4-year condition evaluation

4-year condition evaluation constitutes a summary of the results from previous inspections within the period. The condition evaluation does further comprise an evaluation of said results in order to establish whether the installation may be used with a reasonable degree of safety for the next period.

Concrete Structures

Initial inspection

Initial inspection shall normally comprise:

a) Visual inspection for the localization of surface cracks in highly stressed areas and for potential transportation and construction damages. The inspection areas shall be selected beforehand based on an evaluation of the stress level and shall be cleaned prior to the inspection.

b) Visual inspection for the localization of concrete erosion, primarily in the splash zone.

c) Visual inspection for the localization for corrosion on any steel members.

d) Control/measurements of possible corrosion protection systems.

e) Visual inspection of type, length and quality of marine growth on selected areas at different depth levels (photo documentation).

f) Visual inspection of spots having been repaired during the fabrication, transportation and installation phase. The spots shall be selected taking into due consideration each spot's importance to the safety of the installation.

g) Possible internal inspection when such inspection seems necessary.

h) Visual inspection of the seabed for possible erosion or building up or scour (photo documentation).

Annual inspection

Annual inspection shall be based on the results from the initial inspection. However, the annual inspection shall normally comprise:

a) Inspection as mentioned in the items above (a - h).

b) In addition to the visual inspection for localization of concrete erosion in the splash zone, specific areas shall be cleaned beforehand for visual inspection and photo documentation.

c) The specific requirements (a - h) outlined above shall be implemented, however, such that the photo documentation shall comprise the same area as inspected during the initial inspection.

4-year condition evaluation

4-year condition evaluation constitutes a summary of the results from previous inspections within the period.

Risers (Splash Zone Included)

Initial inspection

This inspection is meant to be a control of the riser in those instances where the time interval from installation to start up exceeds 2 years. Inspection shall, in this case, be carried out after the first winter season following the installation. The extent and type will be evaluated for each individual installation taking into consideration:

a) Condition record

b) Environmental loads

Initial inspection shall normally comprise:

a) Visual inspection of the riser with accessories for localization of mechanical damage, possible metallic waste in contact with or in the immediate vicinity of the installation.

b) Visual inspection of the fastening device with testing tightness of the bolts for riser clamps. The torque shall be in accordance with the approved design specification.

c) Visual inspection of fastening device for anodes and potential readings of the corrosion protection system.

d) Control for verifying that the riser on the seabed is in accordance with the approved design specifications.

e) Control of the riser's horizontal/vertical position.

Start-up inspection

Start-up inspection shall normally comprise:

a) Inspection as mentioned in items a - e above.

b) Localization of corrosion. If corrosion is detected, a thickness measurement of the corroded areas shall be performed and photos taken in those areas having been most exposed for corrosion.

c) Visual inspection of the seabed for possible erosion or build-up of scour (photo documentation).

d) Visual inspection of type, length and quantity of marine growth or selected areas at different depth levels (photo documentation).

e) Pressure test of possible external protection device in the splash zone.

f) Verification of all weld tests and possible NDT-tests being satisfactorily completed.

Semi-annual inspection

Semi annual inspection shall comprise:

a) All items as mentioned for the inspection prior to the start up.

b) Visual inspection of any fender device in the splash zone for detection of mechanical damages and possible corrosion.

Pipeline Systems (Underwater)

Initial inspection

Initial inspection shall normally comprise:

a) Visual inspection of the pipeline system with mechanical couplings for detection of any unsupported span, mechanical damages of importance to the safety of the pipeline system. Any unsupported spans, mechanical damages, shall be documented by videotape or equivalent.

b) Control measurements of burial depth at specific intervals.

c) Detection of current conditions which may effect the pipeline system.

d) Internal inspection by use of calibrating pig or other acceptable methods for the detection of changes in the pipeline diameter.

Start-up inspection

The start-up inspection is meant to render a complete status of the pipeline system including mechanical couplings and bottom conditions enabling an evaluation whether the pipeline system may be put into operation in a safe manner.

The start-up inspection shall normally comprise:

a) Inspection of the pipeline by using the best available method--taking into consideration the location of the pipeline, etc. and which ensures satisfactory data for observing the burial, detection of possible unsupported spans. Unsupported spans shall be documented by use of videotape or other acceptable methods.

b) Measurement of the distance between mechanical couplings and concrete coating.

c) Potential readings of the pipeline where this is possible.

d) Internal inspection as described in item d (initial inspection).

Annual inspection

Annual inspection shall be based on the results and experiences from previous inspections. In addition, due consideration shall be taken to the operational conditions the installation has been exposed to, such as thermical exposures, internal pressure and environmental loads.

Annual inspections shall normally comprise:

a) Visual inspection as mentioned under start-up inspection (items a - d).

b. Control by use of NDT-log or other acceptable method.

4.4 Denmark

Danish interests in Arctic oil and gas production reside in their relationship with Greenland, for whom Danish authorities provide technical assistance, in addition to policy and regulatory advice. Rules for drilling in Greenland waters have been developed by the Greenland Technical Organization (GTO) in close cooperation with the Petroleum Directorate of Norway and the Canadian Departments of Energy, Mines and Resources and Indian Affairs and Northern Development. At this point in time each pipeline in Danish waters is addressed on a case-by-case basis regarding pre- and post-installation inspection. Since there are so few pipelines in service at this time formal rules and regulations have not been written. Arctic inspection requirements have not been developed at this time and until production offshore Greenland becomes a reality, it is unlikely that steps will be taken in this direction.

4.5 Offshore Operators

Arctic offshore operators queried during this study unanimously agreed that the question of underwater inspection was, at this time, premature in regards to production facilities, pipelines and supporting equipment. At present the major emphasis regarding production facilities entails identification and/or design of candidate platforms and techniques for their installation and maintenance. Inspection subsequent to installation, although also unanimously acknowledged as an important aspect, is for future rather present consideration. Until the methods and materials of production and transportation have been developed, it is not, in their view, realistic to draw up an inspection program with any great degree of detail.

Although the Arctic may present inspection problems unique to that environment, U.S. operators generally follow the guidelines recommended by the American Petroleum Institute's API RP 2A which, in Section 8, entitled Surveys of Fixed Offshore Structures, recommends the following.

> General. Periodic surveys during the life of the structure should be conducted to detect any evidence of damage, to monitor the adequacy of the corrosion protection system and to plan remedial measures if required.
>
> Yearly Surveys. The splash zone region of the platform should be visually inspected at least yearly to detect possible deterioration from corrosion or damage from vessel collisions or floating debris. This survey should also include a general examination of all above-water structural members, concentrating on the condition of the more critical members such as deck legs, deck trusses, etc. Supplementary means of inspection (e.g., ultrasonic, radiographic, etc.) should be used in addition to the visual inspection whenever required. The effectiveness of the cathodic protection system employed should be checked within a year after the platform installation, and as often thereafter as required to insure adequate protection.
>
> Additional Surveys. A more detailed survey should be conducted on all major platforms following exposure to severe loading conditions, but at least once every five years, unless experience indicates that a longer interval is sufficient. Exact intervals for conducting such surveys should be based upon the type structure, its age, condition, loading

history, and results of previous inspections. The platforms should be thoroughly inspected both underwater and above water for the following:

a. Overall structural condition

b. Cracks and corrosion loss (checks to be made as required by visual, spot ultrasonic or spot radiographic means)

c. Bottom conditions (evidence of scour, instability, etc.)

d. Boat and barge damage

e. Effectiveness of cathodic protection system

f. Changes in the platform (or in the loading) which may adversely affect the structural integrity of the platform

Records. Records of all surveys should be made and retained. The records should contain a detailed account of the survey and include all photos, readings, etc. taken during the survey. Particular emphasis should be placed upon descriptions of any damage noted. Engineering evaluations of the condition of the structure should also be included, as should a detailed description of the results of any remedial measures taken.

Specific inspection programs as pursued by individual operators are detailed in the previously mentioned publication by Busby Associates (1978).

4.6 National Research Council Recommendations

In 1979 the Committee on Offshore Energy Technology of the Marine Board Assembly of Engineering, National Research Council published an assessment of the requirements and methods for the in situ inspection and monitoring of fixed, steel-constructed oil and gas drilling and production platforms on the OCS. The committee's recommendations to the Dept. of the Intertior, for whom the assessment was conducted, included, in part, the following:

Platforms:

- Adopt and implement an inspection program, including monitoring of the corrosion protection system and using the concept of inspection categories 1, 2, 3, for platforms. The program should include the basis for determining events that precipitate Category 2 and 3 inspections.

Platform Risers:

- Implement a visual inspection program above the water and in the splash zone of platforms concurrent with the inspection procedure.
- Implement an underwater visual inspection of risers concurrent with underwater platform inspection. The inspection should examine coatings, attachments, protective structure, displacements, and evidence of leads. If necessary, supplemental inspection for inter-

nal corrosion or erosion may be required. Cathodic protection measurements are necessary at least on an annual basis.

The inspection programs included under the three categories are defined below.

Category 1 attempts to satisfy the need for both major types of inspection after an established period and after a potentially damaging event. The inspection is to be made visually over the splash zone and above-water parts of the platform. Damage or degradation of these sections is evidenced by (i) deterioration of protective coatings, (ii) deformation or other gross evidence of accidental or environmental overloading, and (iii) fatigue cracks caused by environmental or other loads unaccounted for in the design.

Category 2 inspections are made by divers or remote TV (i) if the Category 1 inspections indicate possible damage to the submerged structure, (ii) if available environmental information is deficient or if there has been an extension of technology for which there is little related experience, (iii) after an accident that may possibly have damaged the underwater portion of the structure, and (iv) to detect scour or bottom erosion. In cases ii, iii and iv, the need for Category 2 derives from questions raised in the verification process. In such an instance, Category 2 inspection should be made at least twice, with an interval of about five years between each inspection. Continued inspection should be contingent upon review by the government establishing the need for prolonged observation.

There are three considerations relating to the sufficiency of data obtained by this category of inspection. First, visual observation will reveal evidence of substantial overloading from severe environmental events or accidents by the deformation of a member or joint, the presence of debris, or the changes in the ocean bottom adjacent to the platform.

The second relates to cumulative fatigue loading. No practical means are presently available for measuring how long a structural joint can withstand certain repetitive loadings before it cracks. Visual inspection for cracks or fractures is the recognized practice on all marine structures. As noted, Category 1 visual inspection for fatigue damage is considered adequate if there is enough redundancy in the structure to maintain safety until a flaw is detectable and can be repaired if necessary. Third, visual inspection is also sufficient for detecting excessive fouling and scour, and for revealing general evidence of any unexpected structural change. In most situations, a visual inspection should reveal or detect deformed joints, buckling members, or twisting that would provide a warning of unsafe conditions and signal the need to initiate more detailed work. If questions remain as to the adequacy of the structure after a Category 2 inspection, Category 3 inspections should be initiated. Given the back-up by Category 3, Category 2 inspection should be sufficient for structures typically designed and built for redundancy.

Category 3 inspections concentrate on the part of the structure that has been identified by the Category 2 visual inspection as needing a more detailed examination. Such inspections, performed by diver or remote TV, call for the part to be cleaned as needed beforehand in order to determine the nature and extent of repairs or to resolve any questions raised by the previous Category 2 inspection. Information such as crack length, propagation rate, or crack termination may be essential to a decision on repairs and should be collected. To facilitate the examination, nondestructive testing may be added as appropriate. This category of inspection should identify the need for corrective action and provide the information for design of the remedial measures.

5.0 NDE EQUIPMENT AND DEPLOYMENT TECHNIQUES

Non-Destructive Examination of structures can be performed externally (visually or by using various magnetic and ultrasonic devices) or internally through application of pipeline pigs. For external NDE a variety of techniques are available to carry and employ the device at the examination site, these include divers, remotely operated vehicles (ROVs) and manned submersibles. This chapter identifies and describes the capabilities of the various NDE d vices now available or being developed and also presents the capabilities of the various deployment techniques.

5.1 EXTERNAL NDE EQUIPMENT

Equipment in this category includes visual examination (either directly or by closed circuit TV), photographic documentation, magnetic methods of inspection, corrosion potential (c-p) monitoring, ultrasonic thickness and flaw detectors, radiography and tomography. Visual examination, for obvious reasons, will not be discussed.

5.1.1 Closed-Circuit TV (CCTV)

Underwater CCTV is, after the human eye, the most widely used inspection instrument. There are at least 25 manufacturers of commercial underwater television systems and they offer a wide range of capabilities. Arctic ocean depths, in which drilling is now being conducted and depths in the foreseeable future do not exceed the capabilities of any of the existing units. Similarly, Arctic water temperatures do not present any obstacle. Present CCTVs can be diver-held, manipulator-held, or carried on an ROV.

Most of the early cameras were based on the Vidicon tube, later the silicon diode, the Chalnicon tube and others more suitable for underwater application were employed. The SIT (Silicon Intensified Target) camera is very popular for low light level work. Initially the SIT camera, adapted from wellhead re-entry work, tended to be long, but there are a number now available which are much reduced in size.

Until the late 1970s black and white TV was the standard; more recently color TV has made a significant debut into inspection application. Like its black and white counterpart, early color TVs were existing in-air cameras repackaged for underwater application. Their performance was marginal. More recently color TVs have appeared which are designed specifically for underwater use; their performance is much better but still does not approach the resolution or quality of cine or still photography. The CCD (Charge Coupled Device) camera which eliminates the imaging lines element, appears to be the most significant new underwater TV development. The CCD is rugged, compact and exhibits similar light sensitivity qualities to the silicon diode array camera. It can be used for both color and black and white and with an intenfier for low light applications. The present major limitation with CCD cameras is resolution, but current developments in the U.S. and Japan indicate that within the next two to three years this problem and its high cost will be overcome (Bryan, 1980).

Stereoscopic television is a technique that has been available for the past four or five years but has not yet seen practical and widespread applica-

tion. While the capability for viewing in 3-dimensions is highly desirable, the users of underwater TV have not yet seen it as a competitively marketable product. The reasons for this are not quite certain, but the methods of presenting the 3-D image to the surface operator is often stated as being the severest limitation.

For most applications the transmission of video signals is carried out via an individual coaxial cable or a composite umbilical. Multi-core umbilicals which are rugged and lightweight are available off-the-shelf and can be relatively easily replaced in the event of damage. Fiber optic cables offer the opportunity to carry vast quantities of data over long distances with virtually unlimited electrical noise immunity and appear to be the next generation of cables for carrying video signals. At this point in time at least one ROV employs fiber optics for this purpose. The principal difficulty is in the very practical problems of repairing and splicing which, currently, are unsuitable for routine shipboard application.

Video recordings are made by standard industrial video tape recorders or video cassette recorders, 3/4 inch U-matic format video cassette machines enjoy the greatest present application. Since these are prone to problems, created by humidity and dust, their performance is sometimes marginal at sea. But the problems have yet to prove sufficiently significant for specially designed, seaborne video recorders to be manufactured.

Future developments in underwater TV anticipate the appearance of inexpensive, high-speed, digital imaging processing. This application is designed to enhance inspection of objects. When combined with stereo CCD cameras it will become possible to directly measure and compute 3-dimensional underwater surfaces (Bryan, ibid.). EMI Electronics Ltd., Surrey, UK, has produced, what they have termed, an Underwater Acoustic Television System for viewing objects in muddy or turbid water where optical devices are ineffective. The system consists of a camera unit with external focusing lens and a monitor/control unit interconnected by an umbilical cable. Acoustic waves (2 mHz frequency) generated by the camera are reflected by solid objects and focused onto a pressure-sensitive free plate which converts the waves into electrical energy corresponding to the amplitude of the received signal. The picture information is then fed, via the umbilical, to the display and control unit on the support vessel. The range of the system is a function of the insonification power and turbidity. Typically, for a 4 x 10 watt insonification system good images are reported out to 4 m distance in turbid water. The system has been successfully field tested, but, has not yet seen on-the-job application.

5.1.2 Photographic Cameras

For highest resolution graphic documentation still camera photography is employed. Similar to TV cameras, there are numerous commercial manufacturers of underwater photographic cameras. The principles and techniques needed to produce high quality underwater photographs in both black and white and color have long been known and available. The major drawback has been the considerable expertise required on the part of the camera operator to estimate the correct lighting, f-stop, aperture speed and select the most appropriate film under varying water clarity and ambient light conditions. This problem has been recognized and for the past several years development efforts have been directed toward elimination of judgment factors in the attainment of professional quality

photography. These efforts are aimed at camera systems deployed on ROVs and manned submersibles, as well as diver, hand-held systems. In terms of environmental conditions and water depths, virtually all underwater cameras commercially available for industrial work can cope with Arctic conditions.

In addition to documentation tasks photography can and has been used in inspection tasks to provide, through stereophotography, measurements of micro-topographic relief. Applying aerial photogrammetric techniques to recently developed underwater stereophotography cameras, Turner (1980) reported measurement accuracies of 1:1000 or an equivalent of 0.1 mm in a one square meter field of view. Photogrammetric techniques have been used in the North Sea on several occasions to provide geometric dimensions on damaged or malfunctioning structures in preparation for repair and/or modifications.

5.1.3 Magnetic Particle Inspection (mpi)

This technique is a widely used method of NDE in the North Sea and has been used in the Arctic. MPI is capable of detecting discontinuities (i.e., cracks) at or near the surface in ferro-magnetic materials. Thorough cleaning prior to inspection to at least bare metal is required. To perform conventional mpi the test object is intensely magnetized, and then finely divided magnetic particles are applied to its surface. When properly oriented to the induced magnetic field, a discontinuity creates a leakage field which attracts and holds the particles to form a visible indication of the discontinuity. Magnetic field direction and character are dependent upon how the magnetizing force is applied and upon the type of current used. For best sensitivity, the magnetizing current must flow in a direction parallel to the principal direction of the expected defect. Alternating, direct, or half-wave direct current may be used for the location of surface defects. Half-wave direct current is most effective for locating subsurface defects. Magnetic particles may be applied dry or as a wet suspension in a liquid. Colored dry powders are advantageous when testing for subsurface defects and when testing objects which have rough surfaces, such as castings, forgings and weldments. Wet particles are preferred for detection of very fine cracks, such as fatigue or grinding cracks. Fluorescent wet particles are used to inspect complex objects with the aid of ultraviolet light. Application of particles while the magnetizing current is on (continuous method) produces stronger indications than is obtained if the particles are applied after the current is shut off (residual method). Interpretation of subsurface-defect indications requires considerable experience.

Briefly, the steps involved in mpi are:

a) Clean the surface to be inspected to at least bare metal. This is most frequently performed by a high pressure water jet which may or may not employ grit material.

b) Establish a satisfactory magnetic field in the area to be inspected. Various techniques are available to induce the field, these include permanent magnets or devices such as prods, parallel conductors or coils which require electrical power.

c) Apply ferromagnetic particles to the area. (According to Chidester, 1981, the term "ferromagnetic particles" refers to the iron or iron oxide particles to which fluorescent or non-

fluorescent pigments have been bonded, and which are attracted by magnetism. These are commercially available in various color pigmentations in order to present a contrast to the structure being tested. Some are made apparent using visible light, others may be seen only under ultraviolet light, and some may be seen under both ultraviolet light and visible light.)

d) Measure, interpret and document (usually by photography) the results.

There are several mpi units which are used commercially, some were developed in-house to be used by the developing activity, others were developed to be sold and used by the perspective buyer. Basically, almost all incorporate the following components:

a) A magnetizing device such as described in (b) above.

b) An ink reservoir which contains a special ink mixture and a pressurizing device to push the ink down to the diver.

c) A transformer which converts the electrical supply to a usable shock-proof supply for the ultra-violet light held by the diver.

d) An umbilical which consists of the ink hose, wiring for the ultra-violet and, if used, wiring for the electomagnetic type of magnet.

e) The ultra-violet light itself which is connected to the umbilical and consists of a special waterproof housing and the ink dispensing device which usually is a simple trigger type easily opened and self closing.

A commercially available mpi unit produced by the OSEL Group is shown in Fig. 12. The system pictured includes magnetization prods (coils or cables can also be used), ultraviolet lamp, fluid dispensing system and surface control console, more detailed specifications are presented in Appendix I.

All mpi systems now in use are employed solely by divers. Shallow water mpi produces best results during hours of darkness. When the procedure is carried out in daylight, the ambient light interferes with the ultraviolet light and fluorescent process. With regards to Arctic operations foreseeable water depths are not a problem since the OSEL system can work to 305 m. Winter air and water temperatures might, however, cause some problems since most systems use water to dilute the "ink." Fresh water used as a dilutant may freeze in the -2^{o}C water temperatures and most certainly would freeze at -42^{o}C air temperatures. It could not be determined whether or not an oil-based or anti-freeze ink is available.

5.1.4 Magneto-Marine Method (Fig. 12)

The Magneto Marine Method is a non-destructive defect inspection and evaluation method based on the magnetic stray flux principle. Magnetized homogeneous ferromagnetic materials guide the magnetic field lines. If there is any inhomogeneity, for example a crack, magnetic field lines are forced to

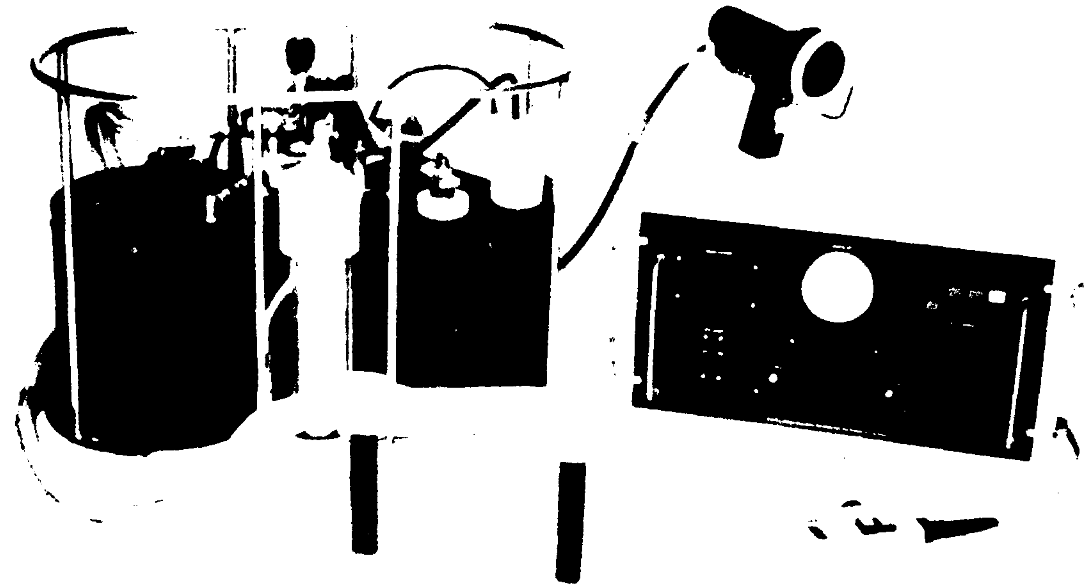


Fig. 12. Top: The OSEL MPI Unit. (courtesy OSEL Group)

Bottom: The Magneto-Marine Yoke for Node Angles from 27° to 90°
(courtesy Magnetische Prufanlagen GmbH)

leave the material and form a stray field above the crack. This field deformation is used to detect the surface cracks. The components of the Magneto Marine Recording Method are :

- A flexible magnetic recording tape is slightly stretched over the weld area to be inspected and secured at both ends with small permanent magnets.

- A magnetizing yoke with a spring-loaded, foam rubber-coated foot between the pole shoes is placed on the weld and presses the tape surface and into the grooves. At the beginning of the tape an artificial flaw (Burmah Castrol Strip) can be placed beneath the tape. The magnetization is provided by very short, strong pulses from the yoke, which is forwarded step by step. Due to the magnetization field deformations originating from cracks are recorded onto the tape. The tape is scanned on board the platform or ship.

Defects such as cracks, undercut, weld spatter and porosity are shown in true scale in one plan of view. The system incorporates a signal amplitude measurement on the paper record of the defects. This combination, according to the manufacturer, Magnetische Prufanlagen GmbH, enables the inspector to judge the soundness of the inspected areas and to distinguish between undercut, spatter porosity of low amplitude and cracks of high amplitude. The paper record with all information can be stored and compared with the results obtained in the following inspections. The magnetic tape can be stored to keep a magnetic record or reused for further inspection.

This method can be applied at nearly any position in a dry zone, splash zone or underwater down to water depths of 150 m at present. Two yokes are available, one for node angles from 90 to 180 degrees and one for angles from 27 to 90 degrees. (Fig. 12)

The Magneto-Marine System has, according to the manufacturer, been approved by Det Norske Veritas. Additionally, the manufacturer sees no inherent problems which would prohibit the device for Arctic application, as the present depth of operation can be easily extended and -2°C water temperature should have no ill effects. The system is designed for application by divers, but is capable, with some modification, of being employed by mechanical manipulators.

5.1.5 Fe Depth Meter

The Fe Depth Meter is used to locate and measure the depth of steel reinforcement - or any magnetic material - in concrete structures. The unit is manufactured by C.N.S. Instruments Ltd., London and is operational to a maximum of 200 m depth. The underwater version is designed for diver application, but it has been modified and used from an ROV.

A magnetic field is generated between two poles at either end of a hand-held probe shaped akin to a telephone receiver. (Fig. 13) The meter measures any disturbance caused by magnetic material passing within the magnetic field generated by the probe. The magnitude of the disturbance is indicated on the instrument meter which may be calibrated to read directly in bar size and distance of the reinforcing bar from the probe.

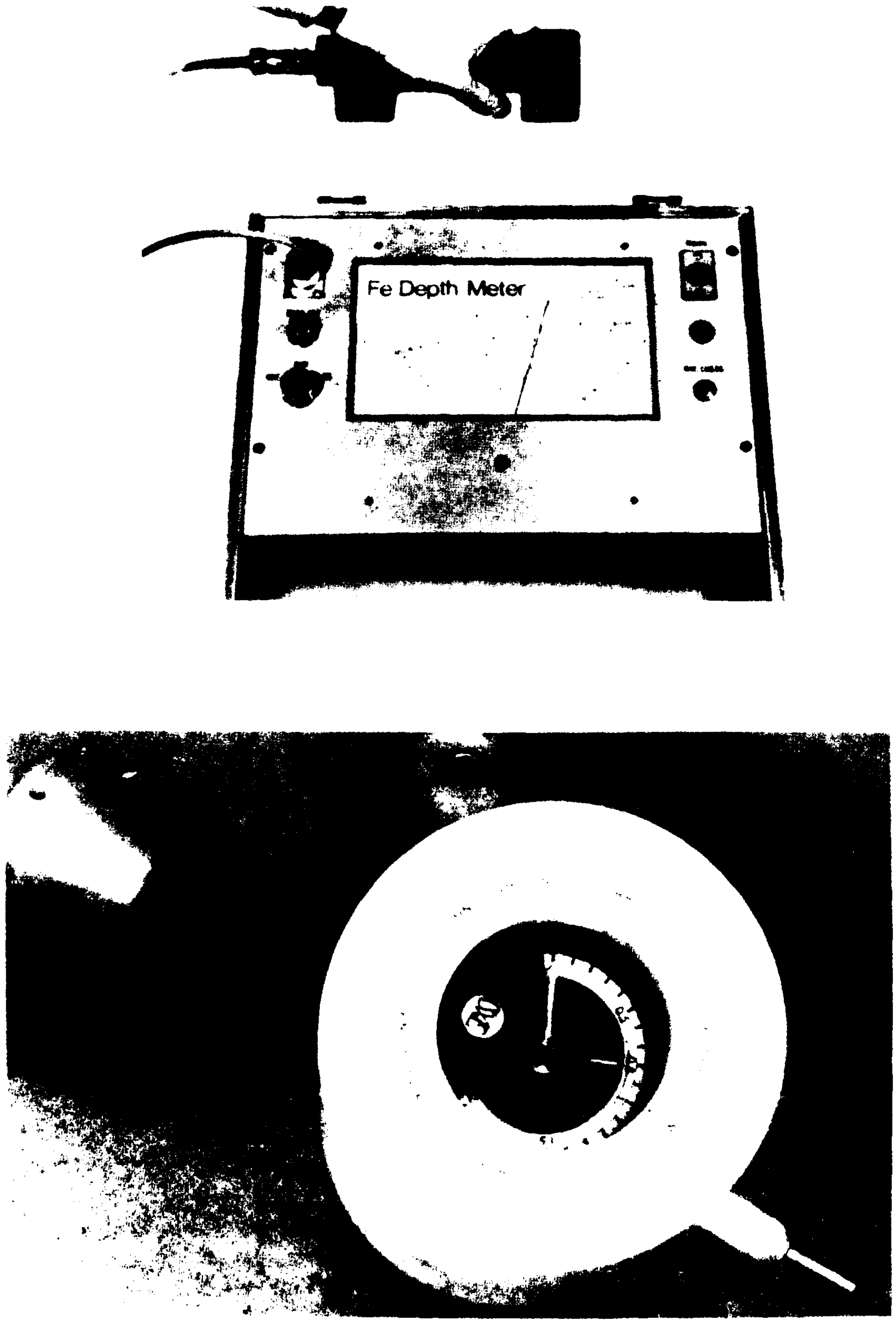


Fig. 13. Top: Fe-Depth Meter. (courtesy CNS Electronics)

Bottom: Bathycorrometer (courtesy Corrosion and Welding Engineering, Ltd.)

A clean surface is required for highest accuracy from the Fe Depth Meter. Data is presented in an analog format; hence it is necessary for the operator to either communicate his readings to the surface or record them by hand at the time. The technique can be used as a measure of concrete erosion, or as a measure of reinforcement corrosion. It is advisable to know the diameter of the reinforcing bar prior to the measurement, although this diameter can be estimated through techniques supplied by the manufacturer. The Fe Depth Meter could be made for application from an ADS submersible or ROV with minor modifications. In such applications the problem of gaining adequate stability to conduct the measurement has been addressed by employing magnetic clamping devices which would hold the vehicle to the structure. The potential obstacle to this approach is that the magnetization induced by the clamps might adversely affect the magnetization induced by the prod. Specifications for this device are continued in Appendix I.

5.1.6 Cathodic Potential (c-p) Monitoring

Regularly scheduled c-p measurements are called for by all inspection requirements. The measurement is taken to determine the effectiveness (i.e., need for anode replacement) of a structure's or pipeline's cathodic protection system. The level of protection is determined by the value of the metal/electrolyte potential. Since it is not possible to directly measure this value a potential measurement is made between a standard reference electrode immersed in the electrolyte and the metal.

Two techniques are currently in use for c-p monitoring, one includes remotely monitoring a permanent reference electrode from which the data is transmitted by hardwire to the surface or through water by an acoustic link. The second technique involves carrying a suitable reference electrode to the anode by a diver or vehicle and making direct physical contact with the anode to obtain the potential reading. For convenience, these techniques are designated remote and direct, respectively, and are described below.

5.1.6.a Remote Monitoring

Two techniques are employed in this type monitoring. The first, which has been used for a number of years, involves attaching reference electrodes to a structure and connecting them to the surface by cables. The earlier versions placed the cables inside conduit pipes for protection; subsequent versions placed the cables inside main structural members for protection. This technique is very straightforward and shall not be further discussed. The second technique is relatively recent, having been first used in 1978, and involves monitoring the reference electrode acoustically thru-water and is described in some detail.

The acoustic monitoring system is termed RPMs (Remote Potential Monitoring System) and was developed by Wilson Walton International for monitoring the cathodic protection on structures and pipelines. In December 1978 it underwent final testing by Shell UK Exploration and Production in the North Sea. The system, described by Chichester, 1978, uses two reference electrodes, one zinc and the other silver/silver chloride. The use of both electrodes provides the operator with the opportunity to check the validity of the data. The remote potential monitoring system comprises a number of self-contained subsea monitors (SSM) and a surface display unit (SDU). Each SSM contains a

zinc and silver/silver chloride electrode connected to an electronic circuit comprised of two comparators, encoder and a transmitter capable of emitting acoustic pulses into the surrounding sea water. The other connections of the comparators are to the watertight SSM housing. When installed the housing becomes electrically common with the steel structure under measurement. The housing is coated with epoxy paint to prevent interference with structure potentials. An internal battery pack provides power for the electronic circuits. The unit is self-contained and can be installed by jacket fabricators or be retrofitted by divers to replace or augment existing cabled installations. It may be placed on a submarine pipeline or located on the sea bed and attached to an adjacent buried line.

The surface display unit is self-powered and is portable. It is used in conjunction with a surface transducer to receive the acoustic pulses transmitted by the subsea monitor. The solution potential information is decoded and presented on two digital displays as reference electrode values. Options exist for data output to a printer or automatic recording device. Usually more than one point of measurement is desired; to accomplish this each SSM is arranged to have an individual code. The codes are generated within the SDU and comprise acoustic pulses transmitted via the surface transducer. Up to 80 codes can be accommodated in a standard SDU. The system is, therefore, essentially a transponding arrangement. After installation of a remote potential monitoring system, the subsea monitors may be interrogated by use of the surface display unit from either a boat or a platform. In each case it is necessary only to come within one mile of each SSM before data may be transferred. A relatively high frequency has been employed since high ambient noise exists around an operating structure.

Operation of such a system in open water presents the least possible problems. Initial performance trials of the equipment in open shallow water early in 1978 confirmed the viability of the concept of remote potential monitoring. Subsequent tests in the Indefatigable gas field 49/24 demonstrated the system's accuracy and reliability to operate on a fixed structure.

5.1.4.b Direct Monitoring

Two techniques have been developed which permit the diver, manned submersible and ROV to conduct c-p monitoring of anodes on structures and pipelines. The first technique involves making contact with a point probe (either single or double) to the metal under test; the second involves measurments of the vertical components of the local cathode protection current density vector over a pipeline without making physical contact. The latter of these two techniques has been developed for application by either a manned submersible or an ROV, but not a diver.

Two point probe devices are commercially available for conducting c-p monitoring, one is the Bathycorrometer MIV developed by Corrosion and Welding Engineering Ltd., the other is the Rust Reader developed by Morgan Berkeley & Co. Ltd. Both devices use a silver/silver chloride half cell. The Bathycorrometer (see Appendix I for specifications) shown in Fig.13 consists of a silver chloride half cell and voltmeter combined in one underwater case. The positive side of the voltmeter is connected internally to the silver chloride half cell and to operate the instrument a connection between the negative side of the voltmeter must be made to the structure under test. This is carried out by means of the probe situated on the opposite side of the handle. A direct reading is then given on the meter, which is illuminated for use in murky or otherwise

subdued lighting conditions.

The two probes are supplied with the instrument, one with a standard point for use on steel work with a thin coating of either paint or insulating tape etc., such as sheet steel piling or undersea pipes with thin plastic tape wrapping. The second probe supplied has an extended point for making contact through thicker coatings or where marine growth has built up . The probes can also be used remotely from the meter by means of the cable extension. This may be necessary where a number of potential readings are required over a relatively small area; the meter can be either held in one hand or rested at a convenient position and the probe used via the extension lead with the other hand.

The Morgan Berkeley Rust Rendar (Appendix I) is similar in configuration, operation and deployment to the Bathycorrometer. However, Morgan Berkeley, as a member of the Corrintec Group, has developed an additional capability which continuously monitors and records the cathodic protection potential profile and radial field gradient along a pipeline utilizing a dual silver/silver chloride probe mounted on an ROV and a silver/silver chloride reference electrode maintained at a distance from the pipeline and support platform.

The system provided by CORRINTEC consists of the following components (see Appendix I for detailed specifications): a probe; remote reference electrode; digitiser; data receiver/monitor; and computer with software controlled data recording.

The probe is the primary data gathering instrument for the survey. Its design, with two precisely located reference electrodes, allows measurement of radial field gradient. A spiked tip permits measurement of pipeline potential and facilitates positive contact with anodes or pipe metal from which calibration measurements may be taken. A shock absorbing bracket attaches the probe to the manipulator arm of the ROV. The bracket design ensures stable contact during measurement of anode and pipe metal potentials and absorbs the stresses placed on the probe during accidental strikes attendant to normal operation. An armored electrical cable connects the probe to the digitiser. A sleeve on the probe and recesses on the digitiser protect the underwater connectors from accidental damage.

The remote reference electrode provides a "remote ground" or reference zero against which to measure the data obtained by the probe. During operation it is positioned 50 to 100 meters from the probe, well away from any electrical fields caused by anodes, the pipe, or the ROV. An electrical cable connects the electrode to the digitiser. Both the electrode and its cable are clipped to the ROV's umbilical.

The digitiser converts the information from the probe and the remote electrode to a digital signal and transmits it through the ROV's umbilical to the data receiver aboard ship. The digitiser is powered by low voltage d.c. via a cable connected to the umbilical junction box. It is secured firmly to the submersible with clamps to prevent movement.

The data receiver/monitor receives the signal from the digitiser via the umbilical. Information arrives at a rate of five times per second, and the digital data is transmitted to the computer for recording. The signal channels for remote electrode and field gradient are, in addition, converted to analogue form and feed a two-pen chart in the recorder monitor to provide a

real-time, pictorial record of changing pipeline potential and radial field gradient. The analogue signal for the potential of the pipeline versus remote electrode is also routed via an offset correction circuit to a digital voltmeter and thence it may be taken to a video writer if desired. This digital voltmeter gives an approximate indication of pipe potential during a dive.

The computer is used to process and record all information relevant to each dive. Information arrives along the link from the data receiver, from the navigation system, from the internal clock, the pipe-tracker, if fitted, and from the computer's keyboard. Under software control, this large volume of data is compressed prior to recording on cassette tapes to maximize the effective capacity of each cassette. All records are linked to time so that any additional information such as corrected navigation fixes recorded during the dive may be added later. In addition to its data recording function, the computer provides a software controlled display of all relevant data channels on its internal digital readout.

The CORRINTEC equipment layout is shown in Fig. 14. The theory of operation is as follows. When a reference electrode connected to a meter is moved along a pipeline, and close to it, it will measure the changing cathodic protection potential, provided the other meter terminal is connected to the pipe. If the normal pipe connection is taken to a fixed potential source, then the electrode/meter system will measure the changing pipe potential in the same way as before, but there will be a fixed voltage offset. The remote reference electrode is used as the fixed potential source, and for this reason it is kept well away from sources of potential disturbance. The recording meter or chart then produces a curve with the potential varying positively and negatively about remote ground. The offset potential is that between the pipe and the remote ground electrode.

In order to calibrate the offset, occasional contact is made with the probe to either an anode bracelet, where available, or bare pipe metal. This calibration is used to give the potential curve a true zero. The two balanced electrodes on the probe, spaced at a fixed separation, measure the radial field gradient. It is essential that the probe is held along a radius line of the pipe, and at a reasonably fixed distance from it, as it is moved along. When the submarine is defined, this geometry is used to calculate anode output currents and damage area currents, as well as general pipe current density.

On clear exposed pipe the vehicle can be fitted with wheels to run along the pipe and provide increased stability as well as an increase in speed. For long sections of buried pipe, a pipe tracker is essential and an indication of the burial depth is required to take into account resistance drops in the mud. The Arctic environment appears to offer only one problem to the CORRINTEC system. The system can be used to -5°C, but below this temperature the reference electrode solution will freeze, although modifications can be made to extend the limit of operations to -10°C (M.S. Reading, personal communication).

A third c-p monitoring device has been developed by ENDECO Corporation, Fig. 14. It is designated the Type 981 Corrosion Detector. According to the manufacturer, the Type 981 Corrosion Detector utilizes new knowledge relative to fish electric field detection and a state of the art Ag-Ag Cl multi-cell logarithmic array with autozeroing and scaling by CMOS microprocessor to allow

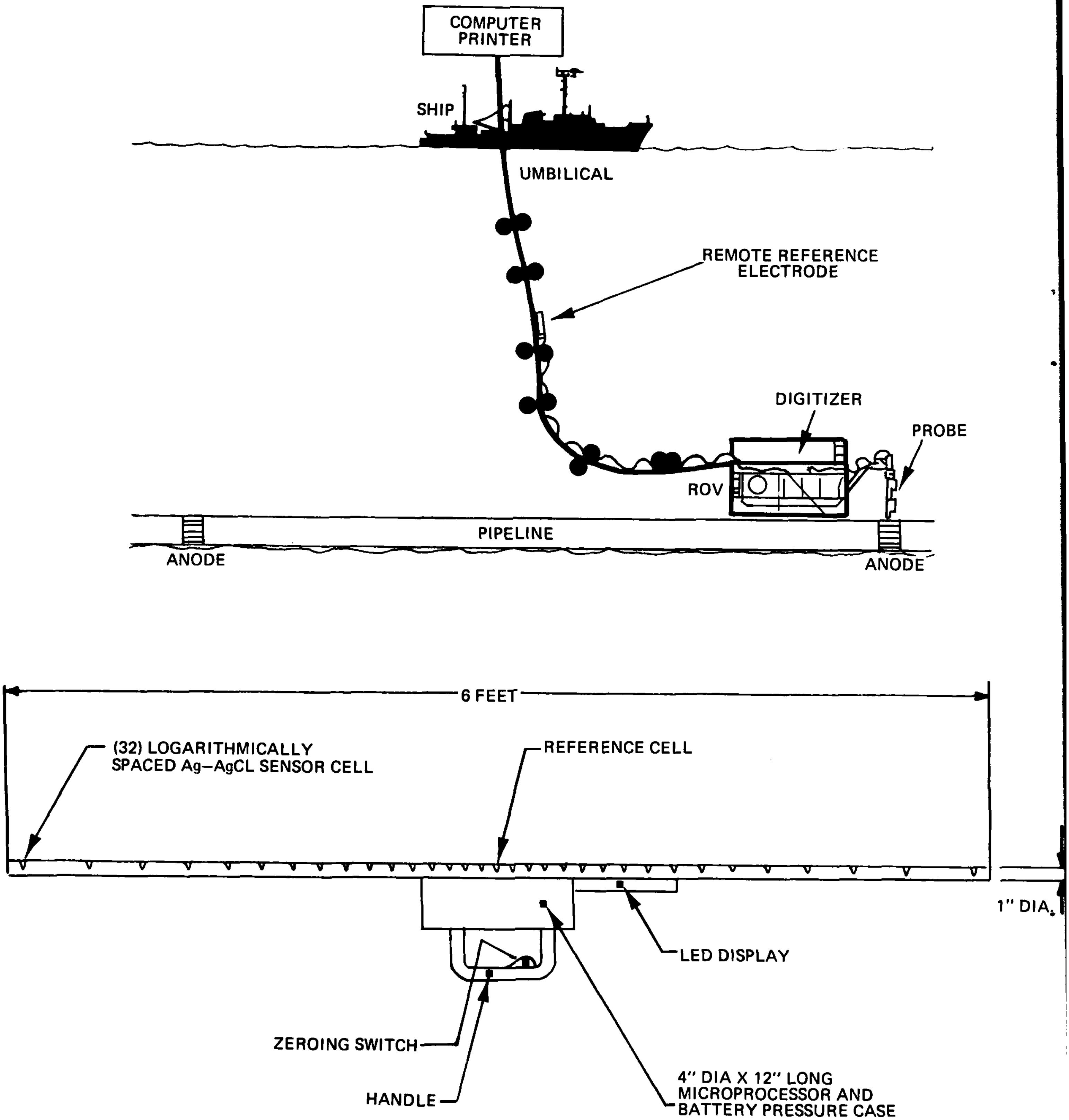


Fig. 14. Top: Components of the Corrintec Remote C–P Monitoring System. (courtesy Corrintec)

Bottom: The ENDECO Type 981 Corrosion Detector. (courtesy ENDECO)

a diver to map out areas of corrosion on metal structures.

During operation a diver grips the handle of the unit. To automatically zero, he holds the unit some distance away from the strucure and depresses an autozeroing control. The self-contained microprocessor automatically compares the 32 Ag-Ag Cl sensor cells to the reference cell and establishes a zero value for each sensor cell. Then, as the unit is moved along the underwater surface of a ship or along the leg of an offshore structure, the microprocessor determines the potential between each sensor cell and the reference cell. This relative potential between sensor cells is then displayed on a logarithmic LED display with the same relative position of 32 LEDs as the Ag-Ag Cl sensor cells of the sensor array.

Since the microprocessor provides autoscaling as well as autozeroing, the light intensity of the LEDs is proportional to the corrosion potentials being mapped by the diver. Since dual red and green LEDs are used, the polarity of the electric field potential is displayed, as well as amplitude. The microprocessor provides autoscaling for fullscale measurements to 1 volt. Electric potentials above 1 volt are sensed, but the LED circuitry is driven to saturation, thus no quantitative information can be obtained at those saturation levels.

The Type 981 Corrosion Detector is neutrally buoyant and fabricated entirely of plastic to prevent interference with the electric field measurements. The unit will operate 10 hours without recharging of the self-contained Ni Cd batteries. Additional specifications are contained in Appendix I.

Intersub Services of Marsille has developed a c-p monitoring system for buried and unburied pipelines which does not require making physical contact between the monitoring device and the pipeline. The system can be used from a manned submersible and an ROV, its two principal components are a current density sensor and a pipe tracking senor (specifications contained in Appendix I) which are shown arranged on a submersible in Fig. 15. According to the developer, the current density sensor is sensitive to current lines which are parallel to the core axis. The two major measurements of interest along a pipeline are the vertical and the horizontal components of the local current density vector. In theory, the vertical current density component should display a positive peak over an anode and be slightly negative over the pipe. Where the insulation of the pipe has broken down a negative current should be induced to protect the pipeline with a peak around -50 mA/m^2. The horizontal component should be zero over an anode and show positive and negative peaks on either side. Operational results showed this to be basically true. However, a detailed analysis of the initial surveys showed that the horizontal component response was on the average significantly smaller than that of the vertical component. It was therefore decided to use the vertical component for routine pipeline inspections as the signal to noise ratio was better and more accurate measurements could be undertaken using this component.

The cathodic protection current is changed into a pulsed DC current by a rotating shutter in the current density sensor. When the shutter is open the DC current flows through and when it is shut the DC current flows round it. This pulsed DC current induces an AC magnetic field in the core, which in turn produces an AC voltage in the detection coil which is directly proportional to the DC cathodic protection current. The exact position of the shutter, driven by a DC motor, is determined by an optical encoder which controls the shutter speed

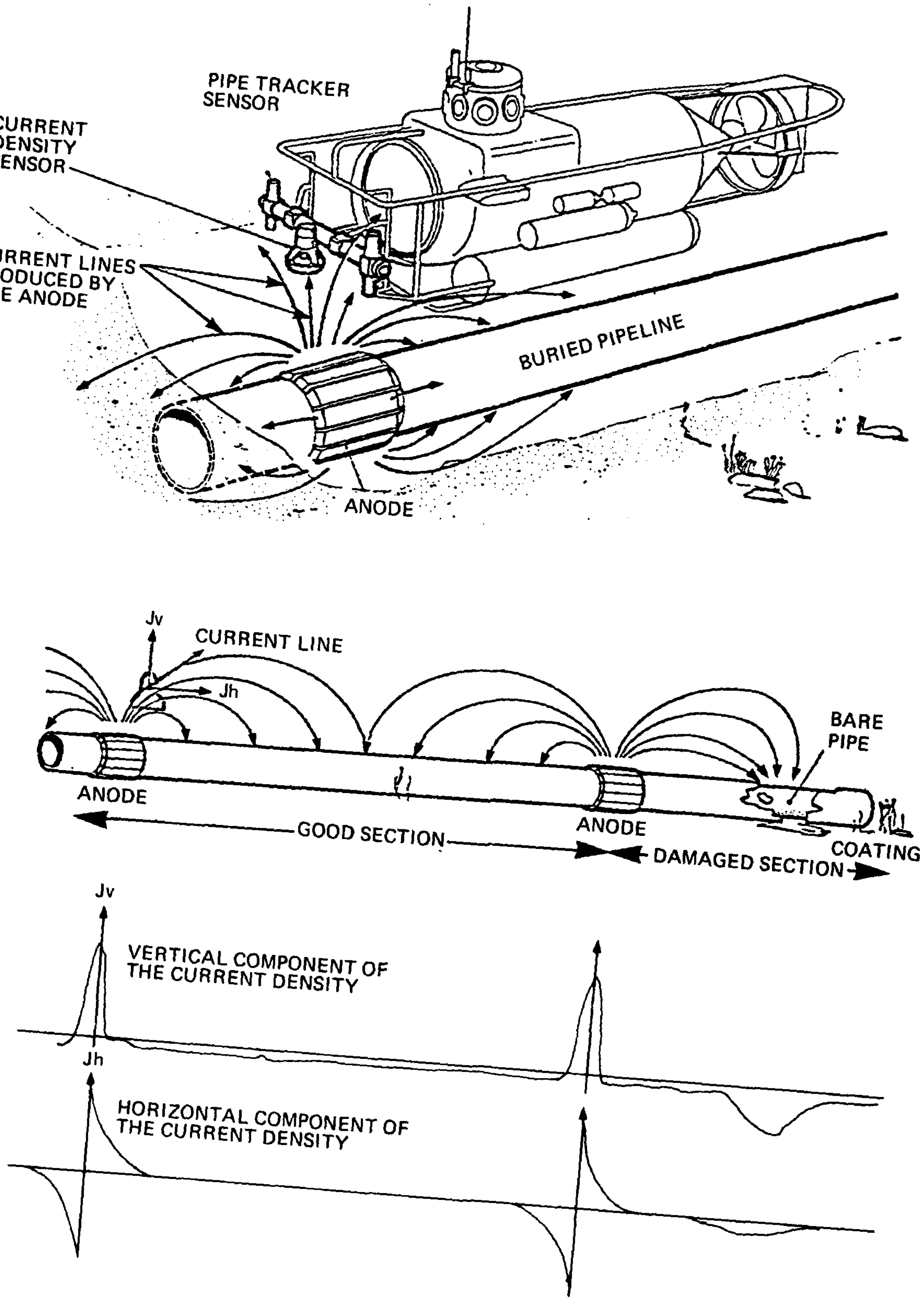


Fig. 15. Intersub Services C–P Monitoring System for buried and unburied pipelines. (courtesy Intersub Services)

via a servo controller thus generating the necessary signals to phase-lock the detection signal. A low frequency AC reference current is generated between two electrodes to calibrate the sensor when required. The AC reference current is phase-locked to avoid interference during calibration. A test box is also provided to check the equipment prior to each dive.

The Current Density System is integrated with the pipetracker through a data acquisition system. The pipetracker provides the distance from the pipe which then allows continuous current density curves to be processed, corrected for distance to center of pipe and integrated into current output. The integration process requires, in addition, the use of a navigation system able to provide position information every 10 to 20 cms. along the pipeline.

The pipetracker system has been used extensively in the North Sea and is based on the principles of electromagnetic induction. A transmitter coil induces an AC magnetic field in the vicinity of the pipeline, thus creating eddy currents in the metallic mass of the pipe, which in return produce another AC magnetic field which is picked up by two receiver coils. The signals from each receiver are mixed and electronically processed to deliver two basic measurements: 1) a signal proportional to the vertical distance between the sensor reference level and the top of the pipe and 2) a signal proportional to the lateral distance between the center of the sensor and the pipe axis including a left or right indication. A careful calibration of response attenuation curves in various laboratory and operating conditions has produced a system which achieves a guaranteed performance accuracy of ±10 cm. vertically and ±20 cm. laterally within the full operating range.

The lateral distance signal is displayed on a central-zero analog meter and is used by the pilot to correct the course over the pipe, or to drive the submersible autopilot which can then track the pipeline automatically. The vertical distance signal must be integrated with an echo sounder and a pressure sensor to enable continuous pipe logging measurements to be recorded. The echo sounder measures the distance to seabed or trench bottom of the sensor reference level, while the pressure sensor measures the absolute depth of the reference level, with respect to the surface sea level. All measurements are simultaneously recorded on a BCD format by the submarine data acquisition system. The measurements are combined to produce the final results. The top of pipe profile is the sum of the absolute depth plus the vertical distance to the top of the pipe. The seabed profile (or trench bottom) is the sum of the absolute depth plus the distance to seabed or trench bottom (as in normal bathymetric surveys). The plot of both curves on a chart, scaled to absolute depth, provides a direct visual indication of the depth of cover over the top of the pipe that can be either positive (pipe covered) or negative (pipe exposed). The resulting continuous depth of cover can also be plotted independently.

The current density system can also be used to inspect concrete platforms. The presence of deep cracks and abnormal porosity are indicated by changes in current density. The metal re-inforcing rods are usually polarized by the concrete, which provides insulation, so normally no current is necessary to protect the metal reinforcing. Only metal exposed to the seawater, such as risers, clamps and exposed re-inforcing are protected by anodes. If, however, the internal metal re-inforcing of the concrete platform is exposed to seawater via porosity or a crack, usually 50 mm. or more, then corrosion occurs and a DC current flows which can be detected in the vicinity of the faulty concrete. A systematic survey

of a concrete structure with a current density system will isolate any significant faults in the concrete. To provide full coverage during the inspection of a concrete platform over a very large surface area, a specialized navigation system is required to ensure no holidays.

5.1.7 ULTRASONIC MEASUREMENTS

Ultrasonics are employed for two purposes in NDE: 1) for thickness measurements and 2) for flaw detection in steel, concrete and wooden structures (or any material which will transmit vibrational energy). Whereas mpi is primarily a technique for detecting surficial defects, ultrasonics is capable of detecting internal material defects. Like mpi, ultrasonics also requires a clean, bare surface for highest accuracy results.

In the ultrasonic method an electric pulse is generated in the test instrument and transmitted to a transducer which converts the electric pulse into mechanical vibrations. The vibrations are transmitted into the object being tested where they are scattered, attenuated, reflected or resonated. A portion of this energy returns to the transducer where it is reconverted to electrical energy and transmitted to the test instrument where it is amplified and displayed, either digitally or on a cathode ray tube. Interpretation of the data for defect presence, sizing, and significance must be conducted by highly skilled ultrasonic NDE technicians. All materials have a characteristic sound velocity which must be known for interpretation purposes, calibration blocks containing variously-sized holes may be employed in situ to calibrate the test instrument. The sound frequency emitted by the transducer for metals testing is high, generally in the range of 3.5 to 5 mHz. For concrete and wood testing it is lower and ranges from 20 kHz to 250 kHz.

Two different test techniques are used in ultrasonic NDE: Resonance techniques and pulse techniques. Resonance techniques are employed for measurement of test object thickness by measuring from one side only. Pulse techniques are used for flaw detection and may be classified as pulse echo wherein a single (transmit/receive) transducer is used, or through transmission wherein two transducers (one transmitter; one receiver) are employed. For underwater communication the pulse echo or single transducer technique is used exclusively. Additionally, two testing methods are used: immersion and contact. In immersion testing the tranducer is separated from the object. In contact testing the transducer is placed directly against the test object, contact testing is used in offshore inspections.

The following is a general description of the ultrasonic thickness and flaw detection devices in underwater use at present.

5.1.7.a Thickness Measurements

There are upwards of ten or more ultrasonic units for measuring thickness. A listing of the various devices and their major characteristics is presented in Table 4 . The principles of ultrasonic measurements have long been known and applied, though not necessarily for NDE, underwater. Consequently, the fundamental approach to underwater NDE thickness measurements is basically the same in all commercially available instruments. (One notable exception being the

TABLE 4 ULTRASONIC THICKNESS MEASUREMENT DEVICES

Unit Designation	Model Number	Manufacturer/ Distributor	Max. Operating Depth (m)	Underwater Components	Normal Deployment Techniques	Dimensions (cm) L x W x H	Weight in Air/Water (kg)	Power Requirements	Temperature Operating Range (°C)
Digital Thickness Gage	UDTM-2	Aquamatic Underwater Developments Ltd.	300	Single unit w/display	Diver	NA	NA/O	Batteries	0-80
Ultrasonic Digital Thickness Gauge	Sea-probe SP200	Baugh & Weeden Ltd.	200	Single unit w/display	Diver	36 x 8.5 dia	1.5/0	Batteries	5-50
Corro-Scan	-	Det Norske Veritas	327	Control Unit/ Scanner	Diver	NA	NA	220VAC	NA
V-Meter	C-4902	James Instruments	NA*	Single unit w/display	Diver	18 x 11 x 16	3.2/NA	Batteries	0-40
NDT Thickness Gauge	701	NDT International Inc.	NA*	Single unit w/display	Diver	3.8 x 8.9 x 15.2	0.75/NA	Batteries	NA
Ultrasonic Thickness Meter	DRUM	Pantation Services Ltd.	350	Single unit w/display	Diver ROV MS	40 x 11 dia	5/1	Batteries	0-70
Ultrasonic Thickness Measuring & Mapping System	AUTA-MAP	Reimers Consultants	61	Transducer	Diver	6.3 x 3.8 dia	0.6/0.45	115V	Normal Temperature
Digital Ultrasonic Thickness Gauge	SP3	Surtest (Marine) Ltd.	200	Transducer	Diver	1.9 dia	NA	Battery	0-100
Ultrasonic Inspection System	Ultra-scan III	Sylvester Underseas Inspection	206	Transducer/ Video Helmet	Diver	NA Standard Size	NA 454 g buoyant	120V, 60HZ	0-50
Ultrasonic Digital Thickness Gauge	5222 UG	Teledictor Ltd.	300	Transducer/ Display/Processing Unit	Diver	NA 17.5 x 27.5 x 10	NA 8/neutral	Battery	0-40
Ultrasonic Digital Thickness Gauge	DM2U	Wells-Krautkramer Ltd.	200	Transducer/ Display/Processing Unit	Diver	NA 20 x 10 x 8	NA 2/0.5	Battery	-15 to 40
Ultrasonic Digital Thickness Gauge	DMU	Wells-Krautkramer Ltd.	200	Gun-Type Display Processing Unit	Diver	31 x 8 dia	NA	Battery	NA

*Designed for surface use; modified for subsurface use.

Corroscan of Det Norske Veritas.) Variations are found, however, in depth capabilities, methods of data display (to the diver or to a surface surveyor), power (batteries vs a surface supply) and data recording (CRT vs digital vs manual recording in situ). The following descriptions are given to present the field at large and variations within; not to discriminate between better or worse. Specifications, where available, for underwater ultrasonic thickness devices are contained in Appendix I.

Self-Contained Devices

Instruments in this category include the Krautkramer-Branson DMU (Wells-Krautkramer in the UK), the Panametrics 5222UG, the Aquamatic Underwater Developments, Ltd., UDTM-2; the Baugh and Weedon, Ltd., SP200, the Pantatron Systems, Ltd., DRUM (a prototype) and the James Instruments V-Meter (a land device modified for underwater use). The characteristics of these devices are as follows:

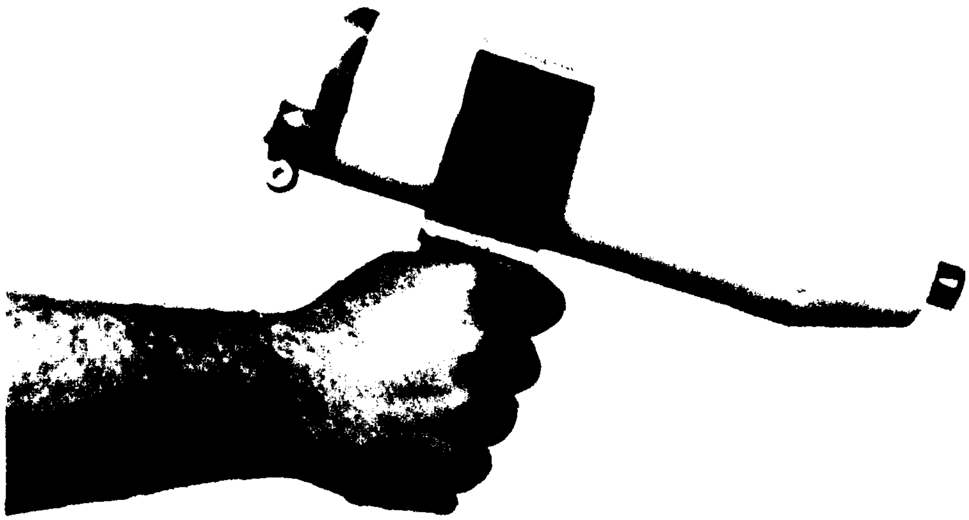
Depth of Operation: 200m to 350m
Power: Internal rechargeable battery pack
Data Display: LED digital
Operating Temperature Range: -15 to 100°C
Data Recording: By diver
Method of Deployment: Designed for diver, but could, with slight modification, be deployed by mechanical manipulation

These instruments are lightweight, easy to deploy and simple to use. The main requirement prior to measurement is to clean the structure of any material which would give spurious thickness measurements. Measurements of steel with thicknesses ranging from 2mm to 300 mm can be made with reported calibration accuracies of ±0.01mm. Representative of the self-contained, ultrasonic thickness measurement devices is the Wells-Krautkramer DMV thickness gage shown in Fig. 16.

Surface-Oriented Devices

Thickness measurement devices in this category are diver-dependent, in that, a diver is required to deploy and control the instrument, but the power is obtained from the surface and the data is telemetered to the surface where it is displayed and recorded. Two instruments will be used to represent this technique: 1) the Autamap TM system of Reimers Consultants and 2) the Corro-scan of Det Norske Veritas.

The Autamap system (Fig. 16) relies upon a diver to position the ultrasonic transducer on the structure and, if necessary, clean the structure prior to measurement. The system consists of the transducer, a surface control console and an umbilical cable (61m length) connecting the two. The unit takes 1000 local readings in 10 seconds and provides automatic calculations of thickness average, standard deviation and per cent thickness reduction from original thickness. Each set of 1000 local readings may be plotted in formats of thickness vs. reading number of thickness vs. frequency of occurrence. These plots permit thickness determinations to be made when severe thickness irregularities may be present. If the transducer is moved in a straight line while the 1000 readings are being taken, the plot of thickness vs. reading number becomes a thickness profile.



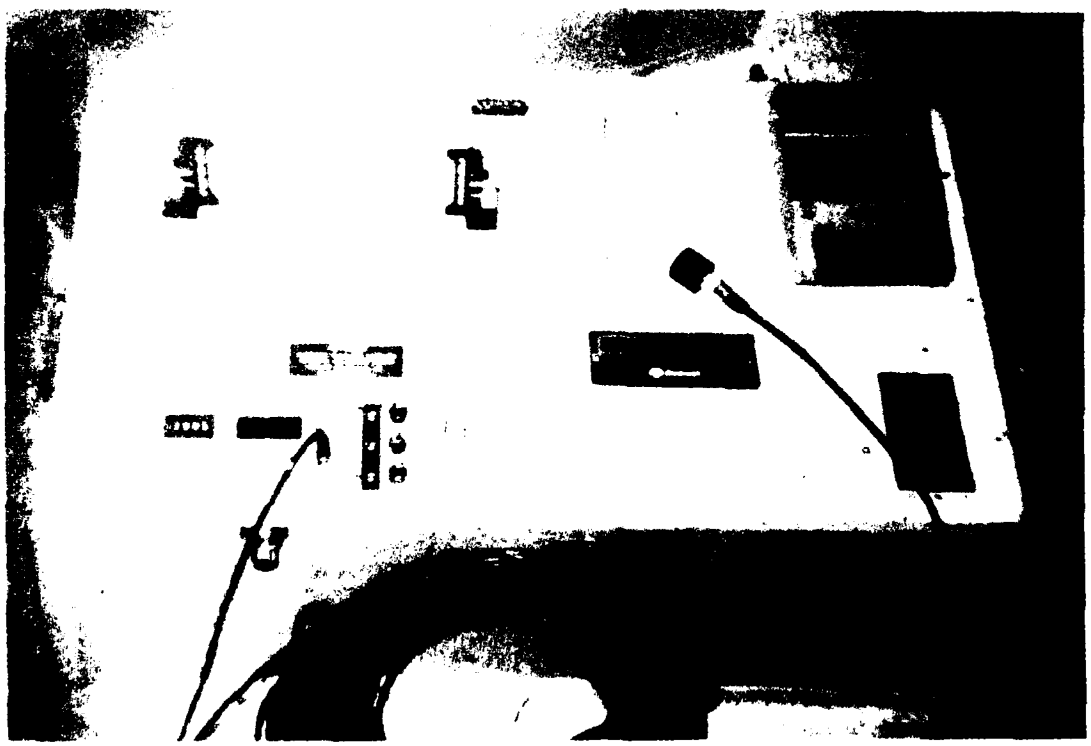


Fig. 16. Top: The Kraut Kramer-Wells DMU Thickness Gage. (courtesy Kraut Kramer-Wells Ltd.)
Bottom: Reimers Consultants Automap System. (courtesy Reimers Consultants)

Thickness average, standard deviation and per cent thickness reduction for each set of local readings may be plotted in serial listing form or in array form where array position corresponds to measurement position.

All data outputs are in permanent hard copy form suitable for subsequent analysis.

Any thickness measuring element that provides an acceptable BCD or analog output to the computer can be used. Systems A and B use standard elements, System C will accommodate any acceptable user-specified thickness measuring element. All systems are designed so that the thickness measuring element can be removed from the Autamap console for independent manual operation.

The Corro-Scan system was developed by Det Norske Veritas and sponsored by Phillips Petroleum of Norway. The system consists basically of three units: a motorized scanner (which is placed on a chain mounted on the pipe to be inspected); a control unit (which controls the movement of the scanner) and a topside data recording and processing equipment. The scanner and the recorder are operated by a diver. When started, the scanner will move around the pipe. Measurements of wall thickness are done by an ultrasonic transducer. Power to the control unit and ultrasonic and position signals are transmitted through cables. A voltage of 220 V AC is supplied to the control unit, and an insulating transformer and equipment for line insulation monitoring is used for diver safety.

The scanner has been designed to operate on pipes with diameter greater than 27.30 cm (10 3/4 in.) and in pipe bends with bend radius greater than 88 cm (32 in.). The scanner can inspect an area of maximum 25 cm length of pipe in one scan. A given movement of the ultrasonic probe along the pipe (y-direction), will result in a certain movement around the pipe (X). The value of X can be changed by mechanical modifications in the scanner. For a probe movement of 250 mm along the pipe it is expected that an X value of 3 mm will be most commonly used, giving a maximum distance between thickness measurements of 3 mm. The ultrasonic pulses may be transmitted with an effective rate of 625 Hz, and the position of the probe will be registered for each ultrasonic measurement. The inspection speed will depend on the scanning pattern and the pipe surface. A typical inspection speed will be in the range 0.12 to 0.04 m/min around the pipe. For a 27.30 cm pipe, a length of 26 cm of the pipe will thus be inspected in 7-20 minutes time.

The Corro-Scan method applied to measure remaining wall thickness on the pipes is an ultrasonic pulse-echo immersion technique. The time between the first front and back wall echoes is recorded. A logarithmic amplifier is used, and measurements can be performed by triggering on edge or peak value of the echoes. A slightly focused 5 MHz probe is used for improvement of lateral resolution and the ability to detect small pittings. Mapping of corrosion by using this measuring principle has been examined and the following accuracies have been achieved:

Depth of inside pit (standard deviation):	0.4 mm
Lateral resolution:	2.5 mm

Measuring wall thickness with pulse-echo techniques is limited to thicknesses above a certain level, this level being determined by the ultrasonic

probe, the signal amplifier and the electronics measuring transit times. For the present system wall thickness down to 8 mm can easily be measured and with careful choice of ultrasonic probe and ultrasonic signal level, wall thickness down to 6 mm can be measured. For thicknesses below this level erroneous or missing registrations may arise.

The inspection data is stored and displayed by using the "T-scan technique" (Thickness image SCANing technique). In this technique wall thicknesses with corresponding probe positions are recorded. Thickness topography is then visualized in two planes. One plane parallel to the surface (Top view) and one normal to the surface (Side view). The top view shows areas with measured wall thickness less than a given level called the display level. The side view shows all thickness measurements projected into one plane, and the display level (given in % of nominal wall thickness) is indicated in this plane. By varying the display level a complete map of the thickness topography is obtained. Two different display levels can be used simultaneously showing areas of wall thicknesses less than the two levels with different colors. At present, underwater components of the Corroscan system are operational to 320 m depth, (Fig. 17).

5.1.7.b Flaw Detection

Similar to thickness measuring devices, ultrasonic flaw detection devices are many and varied and are all primarily designed for diver application. A listing of the various flaw detectors which are commercially available and under development is presented in Table 5 . Summarizing this table the following characteristics apply to the instrumentation:

Depth of Operation:	100 m to 300 m
Power:	Battery Pack and Surface-Supplied
Data Display:	CRT
Operating Temperature Range:	-15 to 80°C
Data Recording:	Data generally relayed to surface via umbilical
Method of Deployment:	Diver-designed, but possible to use with mechanical manipulation

Also like other ultrasonic devices, the devices are lightweight and prior to their use the structure must be thoroughly cleaned. Unlike thickness measuring devices, the data generated by the flaw detection devices is most always telemetered to the surface and displayed and recorded thereupon. Owing to the high degree of expertise required to interpret this data, the interpretation is best conducted elsewhere than underwater and by other than divers who are not generally trained or sufficiently experienced.

The following is a brief description of the various ultrasonic flaw detectors available or being developed for underwater NDE.

Ultrasonic Flaw Detector (Model PA1011)

Manufactured by Baugh & Weedon, Ltd., the system is deployed and read in situ by the diver. It is an A-Scan display and used for detection of cracks, laminations, weld defects, as well as material thickness measurements. A wide range of controls are available in addition to calibration blocks and compression

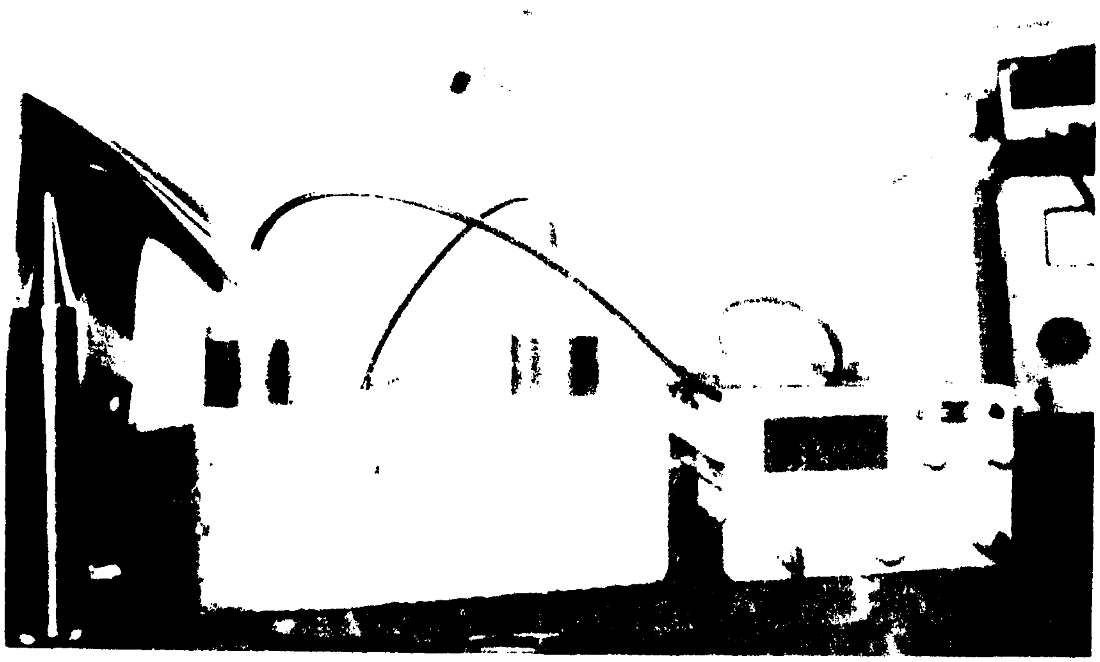


Fig. 17. Top: Det Norske Veritas' Corroscan System. (courtesy DnV)
Bottom: The Pundit System.

TABLE 5

ULTRASONIC FLAW DETECTION DEVICES

Unit Designation	Model Number	Manufacturer/ Distributor	Max. Operating Depth (m)	Underwater Components	Normal Deployment Techniques	Dimensions (cm) L x W x H	Weight in Air/Water (kg)	Power Requirements	Temperature Operating Range (°C)
Ultrasonic Flaw Detector	PA1011	Aquamatic Underwater Developments Ltd.	300	Transducer/ Display/Processing Unit	Diver	NA 25 dia	NA 20/0	Battery	0-80
Ultrasonic Flaw Detector and Probe	PA1011	Baught & Weeden Ltd.	150	Transducer/ (Probe) Display Processing Unit	Diver	NA 13 x 18 x 27	NA 20/0	Battery	-15-50
Underwater Pulse Velocity Tester	Pundit	CNS Electronics Ltd.	300	Transducer/ Display/Processing Unit	Diver ROV MS	NA 20 x 30 dia	NA 16/0	Battery	0-45
Underwater Butt Weld Inspection Instrument	Crack Detector	Penatron Systems Ltd.	100	Probe Pre-amp	Diver ROV MS	11 x 5 dia 43 x 11 dia	250g/o 5/1	Battery (option)	0-70
Ultrasonic Inspection System	ULTRA-SCAN III	Sylvester Underseas Inspection	200	Transducer/ Video Helmet	Diver	NA Standard Size	NA 454 buoyant	120V/60HZ	0-50
Ultrasonic Flaw Detector	USM2	Wells-Krautkramer Ltd.	200	Display/Processing Unit/ Transducer	Diver	35 x 70 x 25 NA	1812 NA	Battery	-15 to 40

and angle pulses. Using the basic PA1011 system, Aquamarine Underwater Developments, Ltd., has developed a flaw detection device with twice the depth range, slightly varying geometry and the ability to operate at higher ambient temperatures.

PUNDIT (Fig. 17)

PUNDIT (Portable Ultrasonic Non-destructive Digital Indicating Tester) is manufactured by C.N.S. Electronics Ltd., London and reportedly has been reconfigured for application from an ROV. The PUNDIT system was developed for concrete testing and consists of the testing unit and one transmitting and one receiving transducer. A variety of transducers are available for frequencies ranging from 24 kHz to 1 mHz, but 50 kHz is considered most appropriate for concrete testing. The data obtained is a digital display of pulse velocity between transmitter and receiver (the exact distance between the two transducers must be known). The indirect transducer arrangement (both transducers on the same plane) is more applicable for testing underwater concrete structures than is the direct arrangement (transmitter and receiver on opposite sides of the test specimen) as access to both the internal and external side of the structure is not feasible. Since the ultrasonic pulse is scattered by discontinuities or large air voids in the concrete, the PUNDIT will indicate the time taken by the pulse which circumvents the void by the quickest route.

The PUNDIT method may be applied to plain, reinforced and prestressed concrete whether it is precast or cast in situ. The measurement of pulse velocity may be used to determine: concrete homogeneity; the presence of voids, cracks or other imperfections; changes due to time (i.e., hydration) or chemical attack, and concrete quality relative to standards which can be related to strength. Interpretation of PUNDIT data calls for a great deal of knowledge and experience.

Crack Detector

Manufactured by Pantatron System, Ltd., the crack detector is a microprocessor-controlled ultrasonic tool for the inspection of butt welds. No flaw signal interpretation is required by the diver. All data is relayed, by an umbilical, to the surface where it is stored. A print-out gives test numbers, wall thickness and defect position in the weld. This instrument is at a prototype development stage at this time.

ULTRASCAN III

Sylvester Underseas Inspection's ULTRASCAN III is equipped with two transducers: one is a conventional transducer (5 MHz) for thickness measurements; the second is a transducer that is shaped to transmit its pulse at 70 degrees to the vertical and is used for detection of flaws or pitting. A digital display is obtained for thickness measurements, while an A-scan (CRT) presentation is used for flaw detection. The diver's helmet has also been modified to support a TV camera, a light and a small TV monitor. The helmet-mounted TV monitor is directly atop the diver's head and a mirror, angled downward, permits the diver to view the TV monitor which is displaying the same picture that the surface test unit is displaying. The surface test unit (a split screen) displays both the results of the diver's transducer measurements and the area being televised by the diver. Consequently, the surface can concurrently see what data the diver is getting and what is the orientation/location of the transducer. This graphic display is relayed back to the diver to allow him to see his results also. As a consequence, communication problems are reduced to a minimum. The surface data can also be stored on video tape for subsequent replay. An additional feature of this system is that directions (via sketches or graphs) can be televised to the diver

and read by him through his helmet-mounted, monitor/mirror system, (Fig. 18).

USM2 - Ultrasonic Flaw Detector

Developed by Wells-Krautkramer, Ltd. (Krautkramer-Branson in the U.S.) the USM2 is essentially a surface device modified for underwater use to 200 m depth. The display is a CRT encapsulated for in situ readings which can also provide data via an umbilical to a surface repeater. The system is battery-operated with an external charging point. A range of underwater-designed probes is available. Approximately 8 hours continuous operation is possible on one battery charge.

Ultrasonic Torch (Fig. 18)

The purpose of the ultrasonic torch is to give a rapid inspection of welded joints to indicate whether they are cracked and, roughly, where the crack is, so that only the cracked places need to be revisited for more detailed examination (Poole, 1980). It consists of a diver-held device which is designed to be held by a large and clumsy glove. All the orientation facilities are built into it, and automated such that the diver simply has to hold it roughly in the right position relative to the weld. The torch puts in a beam of ultrasound to the structure and scans it much like sonar or radar scan to produce a radar-like trace. Inspection is in real time and real-time display can be made on which the weld is seen as a line and any faults as lines in front of it. These faults may still be in the weld metal because the weld reflection is from the root pass of the weld. Typically, on a trace, there is a weld signal and a fault signal, with two lines, front and back, as electronic markers to show the field limitation.

The torch itself is carried by the diver on a 30 m umbilical cable from an underwater relay station which encodes all the data; relays it through an umbilical to the surface where it is displayed on a console. The final display output is in television format so that a video recorder can be plugged into it to get a permanent record. The umbilical comprises a simple power line at 110 volts AC and one twisted pair for the data. The torch is still in the evaluation stage and will be used in the North Sea during the 1982 dive season.

Flexible Belt

This approach has been developed by the MatEval NDT Co., Ltd. and consists of a flexible belt loaded with a number of ultrasonic probes of the correct angle and in the correct positions to detect cracks originating at the outside or inner surface of a node weld during service. It is capable of expansion to provide full ultrasonic coverage of the weld should this be required. The operation is carried out by an ultrasonic technician at the surface, who also controls the whole operation and interprets the test results. The belt is taken underwater by a diver and placed in position. The surface technician can check the quality of coupling and interpret the test results from an array of colored lights.

The belt consists of a number of metal strips linked together so as to be capable of wrapping round a tubular section. Probe mountings are provided on each of the segments which terminate in a pointer. The position of probes within the belt can be adjusted both with respect to the pointer and with respect to

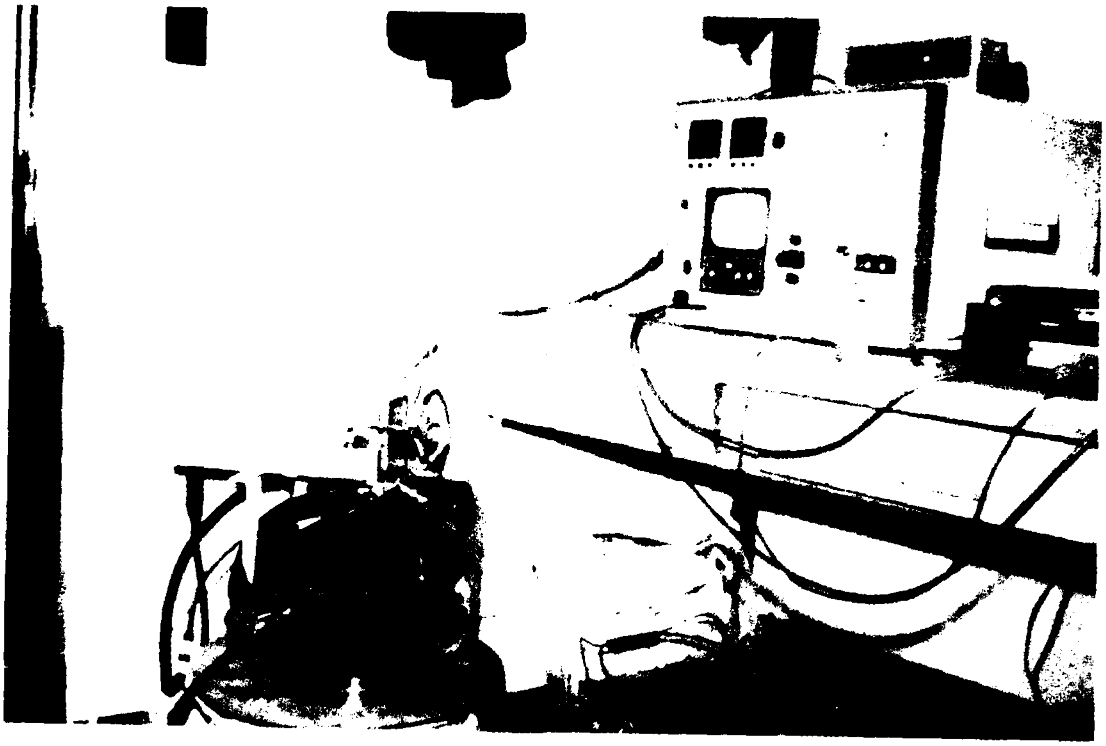


Fig. 18. Top: The Ultrascan III System.

Bottom: The Ultrasonic Torch System. (courtesy Ferranti Computer Systems, Ltd.)

each other. Magnets are provided at discrete intervals, allowing the belt to clamp onto the structure. The cables from each individual probe plug into the decoder. The function of the decoder is to operate each probe in turn as instructed by the multiplexer unit and to route signals, received by the probes, back to the flaw detector. Thus, only a single umbilical joins the pressure vessel to the surface instrumentation.

The pressure vessel and belt are together taken underwater by the diver. The belt is linked to the pressure vessel to prevent undue strain on the probe cables. The pressure vessel is provided with magnets allowing it to be clamped in a convenient position near the working area.

An array of colored lamps, each identified with an individual probe in the belt, indicates the presence of defect echoes in the gate. When a particular probe detects a defect its corresponding lamp lights.

In application, the preformed belt is taken underwater by the diver and placed on the brace in such a way that the pointers make contact with the vertical leg; each probe is thus in the correct testing position. The surface operator fires each probe once, to check coupling quality. When all lights are showing green, the operator can commence the test. Each probe is fired several times by the multiplexer. If defects are detected, a red lamp associated with that probe lights. From the number and position of red lights, the surface operator can estimate defect length. He can also display the 'A' scan of those probes on the flaw detector for further assessment. In practice, several belts would be used to examine a single node. Probably four belts would be adequate for most cases since the object is to facilitate ease of handling by the diver.

5.1.8 TOMOGRAPHY

Tomography, according to Thorne (1981), is derived from the Greek word "TOMO", which means to cut or slice. A tomogram is a cross-sectional slice of an object obtained by the analysis of the transmission properties of radiation. The reconstruction of the properties of matter is accomplished in a computer by calculating the interaction of the radiation with the material per unit volume as observed from various angles of view.

The object is examined as a series of cross-sectional "slices" which are usually displayed by the computer as pictures on a television screen. Each "slice" picture or "tomogram" is formed from calculations based on measurements of the radiation transmitted along several thousand paths through the object. These measurements are made by moving the radiation source and detectors across and around the object being examined in a horizontal plane and the attenuated rays of the beam are intercepted on the other side by a multi-detector array. The photon energy used is chosen to balance the conflicting requirements of adequate penetration (high energy) and maximum density discrimination (low energy).

As the x-ray beam passes through the object, some of the photons are scattered or captured. The percentage of the beam lost to such processes gives a measure of the total matter along that path. A variety of mathematical methods exist to transform the transmission values into a picture of the opacity or electron density values in the slice. These values correspond approximately to the object's mass density. The exact relationship of these values to density depends on the photon energy or energy distribution and the atomic number of

elements in the objects and the object's density. The source and detector system observes a number of discrete mass values during the arc movement about the object and the detection data sets for each arc-scan are stored in computer memory files for later processing and analysis.

A tomographic inspection system is composed of two sub-assemblies: 1) a detector array and photon emitter (which performs the active scanning) and 2) a computer and related peripherals connected by hardwire to a remote location. Once scanning is started, results are seen instantaneously on the television CRT display. Projected features and defects can be scaled directly off of the screen. Pertinent referencing information (i.e., component no., size, orientation, notable defects, etc.) can be printed onto the display and into the data memory for future reference. Multiple tomographs can be recalled and presented at one time on the display in order to "chart" a crack or similar defect. Areas of interest can be expanded as required for further analysis and clarification. The thickness of the slice plane depends on the desired resolution.

The tomograms can resolve features as small as 1 mm and can detect visible features as small as 0.1 mm. Densities can be measured to better than $\pm 1\%$ accuracy. Examination of each slice can be done in seconds, depending on the intensity of the radiation source and the degree of resolution required. Scanning rates can be varied to suit the inspection supervisor's needs. Normally, tomographs are taken and displayed continuously.

Tomography can be used to provide analysis of wood, steel, concrete and various synthetic materials (Ellinger, et al, 1979 and Morgan, et al, 1981). The distinction between tomography and ordinary radiography is that tomograms are maps of electron density. The tomogram is calculated by a digital computer from measurements of the x-ray or gamma-ray transmission projections of the object at many angles in the slice plane. Although each set of measurements consists of projections, in which all the objects along a line are superimposed, the computed tomogram is not a projection, but rather a cross section. A unique feature of this technique, relative to the previous techniques, is that the object of inspection need not undergo cleaning prior to examination. At present, the devices used are for surface application, however, the U.S. Navy Facilities Command is supporting efforts to encapsulate the system for application underwater.

5.1.9 Radiography

The primary underwater use of radiography is for weldment inspection. The advantages of radiographic techniques are that they permit a visual analysis of varied defects (cavities, cracks, porosity, non-metallic inclusions) and a reasonably sharp and clear image is recorded on film as permanent documentation. The technique is also used for thickness measurements. While radiographic techniques are standard and common surface NDE procedures, they are not a common underwater procedure. Several service companies do perform radiographic examination (e.g., Taylor Diving and Salvage, Ocean Systems, Inc., Can-Dive Services Ltd., B.I.X.), details of techniques and instruments employed are considered proprietary.

In most instances radiographic techniques are employed in dry habitats; in this application the techniques are similar to surface techniques. The diver's function is to conduct the test; interpretation is done on the surface by a qualified NDE technician. The depth range of radiographic techniques is equiva-

lent to that of the diver, upwards of up to 500 m, in an ambient pressure, dry habitat. In an 1-atmospheric chamber depth is limited to the chamber's working depth. Can-Dive Services of Vancouver, B.C. has developed a radiographic device which can be used by the diver exposed to the water. It is designed, however, for use on flat, metallic structures, not tubular structures, and for relatively shallow depths.

5.2 INTERNAL NDE EQUIPMENT

Equipment designed to conduct internal NDE of pipelines and risers is generally referred to as pipeline pigging equipment. A list of the suppliers of such equipment and the pigging devices they produce is contained in Table G . By far, the major utilization of pigs is for such tasks as gaging, cleaning, and batching and displacement in pipelines. In terms of NDE, functions such as wall thickness measurements, x-rays of weldments, photography of the pipe and weldments (gas lines only) and mechanical deformation of the pipe can also be obtained. Pigs are designed for use in both oil and gas pipelines where the propulsive force is generally supplied by the product flow while the line is in service.

A variety of mechanical, magnetic and acoustical techniques are employed to track the pig during its traverse of the pipeline. The most basic locationing device is a mechanical probe or trigger which is mounted onto the pipe and extends into it an appropriate distance. Passage of the pig activates the trigger and a signal is generated which can be noted visually by a flag or electronically by some combination of audio/visual effects. Pig location devices produced by the T.D. Williamson Company (Pig-Sig) and General Descaling Co., Ltd. (Pigalert) typify this approach. Acoustics in the form of a pinger attached to the pig can also be used. Helle Engineering, Plessey Co., Ltd. and Heath, Inc. offer acoustic pingers which can be used to locate the pig. The Plessey Company's locater can reportedly locate a pig at distances up to 160 km, but only when the pig is stopped. AMF Tuboscope's approach combines magnetics and measurement wheels. The Tuboscope pig generates a magnetic field which is induced into the pipe and sensors detect changes in the magnetic field due to corrosion or other transverse or 3-dimension defects. Magnets are placed at known intervals which act as reference points on the resultant record. Large objects such as girth welds, valves and welded sleeves also leave characteristic signals which can be used for positioning in conjunction with the magnetics and distance measuring wheels.

There is no single reference which contains details of the many and varied pipeline/riser pigs now in use or being developed. The following narrative attempts to present an overview of this field in terms of NDE. While cleaning and gaging prior to employment of an NDE pig is critical to the operation, a description of the many different types produced by such firms as General Descaling, F.H. Maloney, Mustang Services, Myoco and T.D. Williamson is not warranted. It is sufficient to note that cleaning and gaging can be performed by pigs on virtually any pipeline regardless of diameter.

BIX International

The BIX device is a compact, battery-operated crawler which is remotely controlled and provides panoramic inspection by the use of x-radiography of welds

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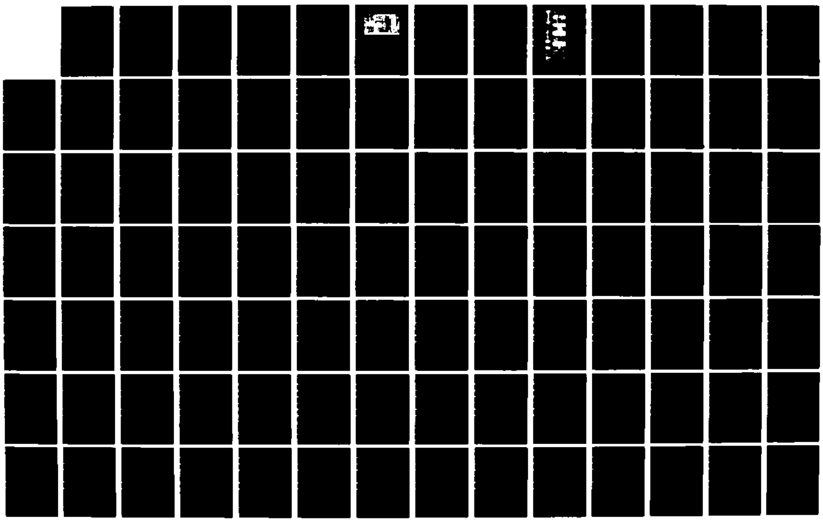
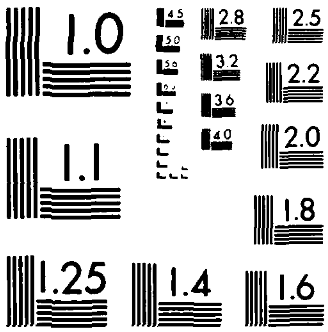




MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

TABLE 6 PIGGING EQUIPMENT PRODUCERS AND DEVELOPERS

Company	Pig Functions
BIX International Leighton Buzzard, UK	x-radiography of pipeline welds
British Gas Corporation Newcastle, UK	Pipeline defects and corrosion
Det Norske Veritas Oslo, Norway	Riser wall thickness
General Descaling Co., Ltd. Workshop Notts, UK	Pipeline gaging, cleaning, separation and deformation and internal/external corrosion measurements
GEO Pipeline Services, Inc. Houston, TX	Internal color photography of gas pipelines
Knapp, Inc. Houston, TX	Cleaning
Magnesonics, Inc. Albuquerque, NM	Detect stress corrosion cracks and wall thickness
F.H. Maloney Co. Houston, TX	Pipeline gaging, cleaning, batching and dewatering
MatEval NDT Co., Ltd Newton-le-Willows, Merseyside, UK	Riser wall thickness, corrosion
Mustang Services Co. Houston, TX	Pipeline gaging, cleaning, batching, dewatering
Myoco Houston, TX	Pipeline gaging, cleaning, batching, dewatering
Oilfield Inspection Services, Ltd. Gt. Yarmouth, Norfolk, UK	x-radiography of pipeline welds
Peabody Testing Services Chicago, IL	x-radiography and photography of pipeline welds and internal features
Plessey Co., Ltd. Ilford, Essex, UK	Pipeline flow rate measurements, leak detection and temporary leak sealing
Select Industries Wichita Falls, TX	Pipeline cleaning
Shell Oil Co. Houston, TX	Pipeline stability and wall thickness

Table 6 - cont.

Tuboscope, Inc. Houston, TX	Pipeline corrosion and defects
Vetco Services Houston, TX	Pipeline corrosion, mechanical damage, gouges, dents, bends, blisters
T.D. Williamson, Inc. Tulsa, OK	Pipeline gaging, cleaning, batching and dewatering

in pipelines ranging from 235 mm to 510 mm inside diameter. The device was developed by Scanray (International Testing), a BIX Company, in 1978 and utilizes a Cadex cine x-ray system which operates at speeds of up to 10^6 frames per second.

British Gas Corporation

The British Gas Corporation's intelligent pig is a heavy duty computer-base inspection vehicle which records all features or defects believed significant to the pipeline's longevity. As of 1981 BGC's pig had logged over 15,000 km of line inspection, but had not, at that time, entered the offshore market. Although details of the vehicle's construction and operation are not available, the sensor system relies on magnetics and acoustics which record variations in both steel and concrete coatings. The device is the result of a 47 million pound (sterling) project developed at BGC's On Line Inspection Center. As of August 1981 the pig had not yet been used in offshore operations owing to the more inherent difficulties in retrieving the device if it were to become stuck.

Det Norske Veritas

DNV's device, called VERIT, is designed to perform wall thickness measurements from the inside of a riser by means of an ultrasonic immersion technique. The vehicle measures wall thicknesses, and will detect general or pitting corrosion areas of a certain extent, determined by the measurement pattern. The thickness is measured with an accuracy of $\pm$ 1 mm or better depending on surface roughness. The pipe diameter (bulges, out of roundness) can be measured with the same accuracy.

VERIT is constructed for operation in a 86 cm (34 in.) diameter pipe, but can operate in 91 cm (36 in.) pipelines and, with some mechanical modification, in other diameter pipes. The wall thickness measurements are automatically stored on tape by a small computer, which also gives the operator a control display of the data. The ultrasonic equipment, a Krautkramer KS 3000 system, also gives a display of the measurement signals, and offers the possibility of manual evaluation of the ultrasonic signals.

Because the measurement principle is an immersion technique, the riser must be oil- or water-filled to conduct the measurements. The vehicle is controlled by an umbilical containing hydraulic hoses and electrical cables. The inspection must be carried out through an open pig launcher or similar opening in the pipe, cable lengths of 250 m are possible.

The propulsion system, which must function inside a slippery vertical riser, is composed of two groups of hydraulic grip cylinders. One group is mounted on the main frame and the other on an axial slide frame. The slide frame is moved axially by a step cylinder. By activating the grip and step cylinders in the proper sequence the vehicle will move inside the riser. The total weight of VERIT is 2000 N (1/5 tonne) and the measured friction force between the grip cylinders and a greased pipewall is about 6000 N in a forward and backward motion. Simultaneous with the step cylinder movement, the scanning arm holding two diametrically opposed ultrasonic probes, sweeps 180 degrees, providing a total probe sweep of 360 degrees for each forward step of 10 cm length. On one sweep 75 measurements are recorded for each probe, or 150 measurements around the circumference.

The longitidunal position in the riser is given by the step number from the pig trap opening. The step number will be calibrated against markers on the cables. The circumferential position is given with reference to the vehicle orientation. This means that the actual twisting of the vehicle will be the limiting factor. On straight pipe the twist is measured to less than $\pm$ 1 degree in 10 m. In bends the twist is dependent on vehicle orientation, but less than $\pm$ 10 degrees for 90 degrees of bend. Referred to longitudinal welds the circumferential position may be given with an accuracy of a few degrees.

The signal processing consists of amplification of the echo signals and digitalization of the time intervals between echoes. The thickness measurements are read into the computer together with the actual vehicle position. The operator chooses the gates within which echoes are expected, and has a direct control over the measurements. He can, from the echo-pattern, determine the presence of laminations, inclusions, bulges, welds, thickness reductions, and determine if the thickness reduction is outside or inside. By changing the signal processing procedures an automatic registration of one or more of these features is possible. The VERIT vehicle is shown in Fig. 19.

GEO Pipeline Services

Developed jointly by GEO Pipeline Services and Magnaflux Corporation, the camera pig is designed to visually examine the integrity of the internal coating inside natural gas pipelines and confirm coating smoothness, bonding and quality.

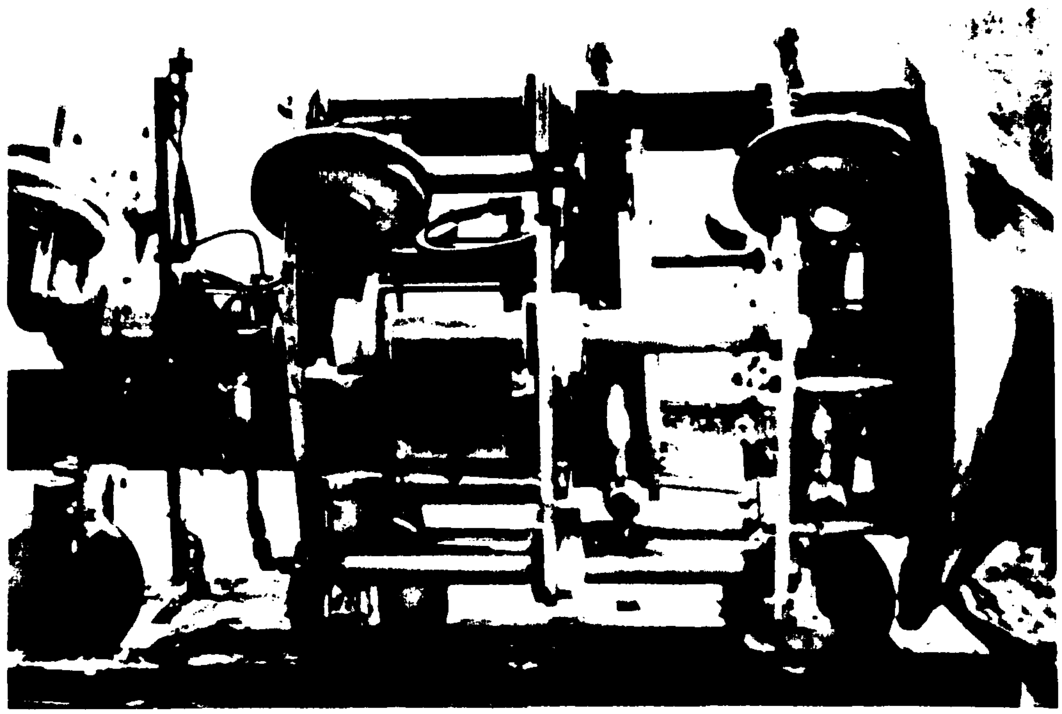
The pig carries a 35 mm camera in an explosion-proof assembly. The camera is designed to operate in pressures up to 114 Kg/cm^2 (1600 psi). It has a wide-angle lens that can cover 90 degrees of the inside wall of a 40.6 cm (16 in.) OD pipe, or 140 degrees of the inside wall of a 91.4 cm (36 in.) OD pipe. The camera pig's shutter and strobe light can be actuated by a timer, footage counter, or weld sensors; its magazine holds enough film for as many as 250 black-and-white or color photographs during a single run.

The camera pig's overall length is 137 cm, enabling it to fit into the launcher and to move through 90 degree bends. In the three-cup tow pig, shown in Fig. 19 , the body is a tube with welded endplates. The tube holds the activated alumina dessicant for the dry gas injection system. A pump injects the dry gas into the camera's viewing area to enhance the environment within the inspection area.

If any liquid gets past the tow pig's two leading scraper cups, a siphon tube transfers the liquid to the front of the pig. The siphon's power is from the pipeline gas, which flows from the rear of the camera pig through a pair of pipes and through open holes in the rear cup of the tow pig. The two front cups on the tow pig are the only active cups, and therefore pull the remaining portion of the camera pig train. The two orienting weights are used to assure that the camera lens is facing downward. A universal joint connects the two pigs.

The camera pig system does away with guesswork when it comes to checking coating on new pipe or old, and when there is a need to check older pipe that might require maintenance and rehabilitation.

Travel is slightly over 1.8 m/second with no interruption to product flow.



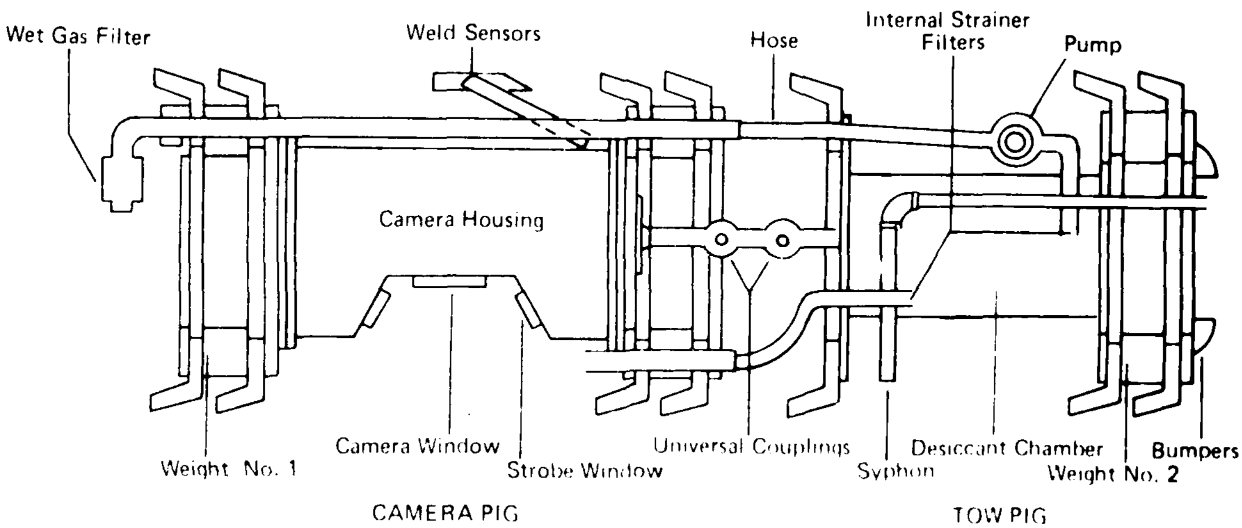


Fig. 19. Top: Det Norske Veritas Verit Riser Inspection Vehicle. (courtesy DnV)

Bottom: GEO Pipeline's Camera Pig. (from Pipeline & Gas Journal, March 1981)

MatEval NDT Co., Ltd.

The MatEval device provides an automatic ultrasonic system for measuring the extent of erosion and/or corrosion in oil risers. The device consists of an oil-tight pressure vessel containing the electronic circuitry necessary to multiplex ultrasonic probes which are recessed into a spring-loaded skid and dirate the pressure vessel. A constant oil gap is required between the probe face and skid surface. The device is connected to surface instrumentation by an umbilical which carries power, data transmission and a hoisting cable. The test head may be driven down through the oil by wheels which contact the inner surface of the riser or by a propeller (i.e., vertical thruster). To conduct the measurements the test head is retrieved by the hoisting cable at a controlled rate taking wall thickness measurements either continuously or at pre-determined intervals up the riser. A computer or micro-processor reviews the signals at the surface and can print out the data in various forms. Regardless of how badly corroded the riser bore may be, each skid takes up a mean surface. By appropriate gating, the distance from this mean surface to the riser bore surface and the wall thickness can be measured. Product flow must be arrested in order to use the MatEval technique.

Oilfield Inspection Services

In 1978 Oilfield Inspection Services Ltd. introduced a pipeline inspection service which employs an automated, self-propelled Mini-Crawler. It is capable of travelling within pipelines down to 25 cm (10 in.) bore taking x-ray photographs of pipeline welds from the inside.

The Mini-Crawler is designed for remote control from outside the pipe. It is completely self-contained, with no connections between itself and the open end of the pipe. It is controlled by use of a small radioisotope source which emits a collimated beam of radiation through the pipe wall. This control isotope is precisely positioned at the pipe weld to await detection. The operating parameters of the x-ray head of the Mini-Crawler are pre-set so that the x-ray head is centralized and x-ray power is set to suit pipe wall thickness. By moving the control isotope in a predetermined sequence, forward, reverse, and park x-ray functions can be selected. Once the crawler is in position at the plane of a weld, an x-ray film is wrapped around the weld. The stationary isotope is then removed and after a safety delay the x-ray tube is fired. The isotope is then positioned at the next weld and the procedure repeated.

The crawler is powered by a rechargeable battery which lasts for about [illegible] butt weld x-rays on 40.6 cm (16 in.) pipe on a single charge. Changing batteries takes two minutes including drive and x-ray test cycles.

Built-in safety devices guard automatically against runaway of the crawler and in case of operational failure, a compressed air recovery vehicle can be sent down the pipe to latch onto the crawler and bring it to the pipe end.

abody Testing Services

eabody has developed some [illegible] pipeline crawling machines which are used to obtain [illegible] degree x-rays of pipeline weldments. The crawlers are self-powered and portable and can inspect pipes ranging in diameter from [illegible] to [illegible] cm ([illegible] to [illegible] in.). [illegible] loaded into the pipe the unit is turned on and automatically

travels the length of the pipeline section, stopping at each weld to take a radiograph. As presently designed they are not applicable to underwater use. Peabody has also developed a pig which can take 750 photographs of 305m of pipe from the point of entry at the lay barge on 407 cm (16 in) and 97 cm (36 in) diameter pipe.

Plessey Co., Ltd.

Plessey has developed a pipeline pig for detecting pipeline leaks and to temporarily stop the leak. The pig is inserted in the leaking pipe which is then pressurized and sealed. It then travels along within the pipe under declining pressure to the leak site, at which point the flow reversal brings the sealing action into effect against the inner wall of the pipe. The pig also carries instrumentation for measuring flow-rate and direction and for transmitting this data to the surface. The flow-rate measurements are carried out on either side of the leak until the section where leaking is occurring is identified.

Shell Oil Co.

Details on the shell pigging device are not available. However, according to Mr. R. Geer (Shell Oil Co., Houston, personal communication), Shell is developing a pig to observe corrosion in both pipelines and risers. A great portion of this development is aimed at Arctic application. The device, when developed, will be made available to other offshore operators under a yet-to-be developed leasing program.

AMF Tuboscope (Fig. 20)

AMF Tuboscope developed their first instrumented pig, the Linalog tool, in 1965. At this point, reportedly over 112,000 km of pipeline have been inspected with diameters from 15 to 101 cm (6 to 40 in.).

The Linalog tool has three basic sections (R. L. Swick, unpublished manuscript): drive, sensor and instrumentation. These are connected by universal joints so that the pig can negotiate bends with a minimum radius of three pipe diameters. The forward section of the pig is designated the "drive" section and houses the batteries needed to drive the electronics. This section is fitted with scraper cups that serve to center the pig in the pipeline and form a seal with the pipe wall, permitting the flow of natural gas or liquid petroleum to propel the unit. The second section is called the "sensor" section. It is equipped with two banks of transducers arranged to assure full circumferential coverage. While surveying the pipeline a magnetic field is induced into the pipe and any changes in pipe wall thickness are detected through changes in the magnetic field (leakage), and then transmitted to the instrumentation section. The rear, or third section of the pig carries the recording instrumentation. Amplifier circuits and the magnetic tape recorder are inside this section. The power supply and recording components are designed for 24 hours running time, however, an extra battery pack can be attached on small linalog tools ranging from 15 to 41 cm (6 to 16 in.) to exceed the 24 hour limit.

Several steps are taken prior to the start of the actual instrument survey run. Large horseshoe magnets are placed at approximately 900 m intervals to provide reference marks on the survey chart. The indications on the log from these marks serve as tie-points between the pipeline and the log. This permits location of the corrosion pitting by scaling the distance on the

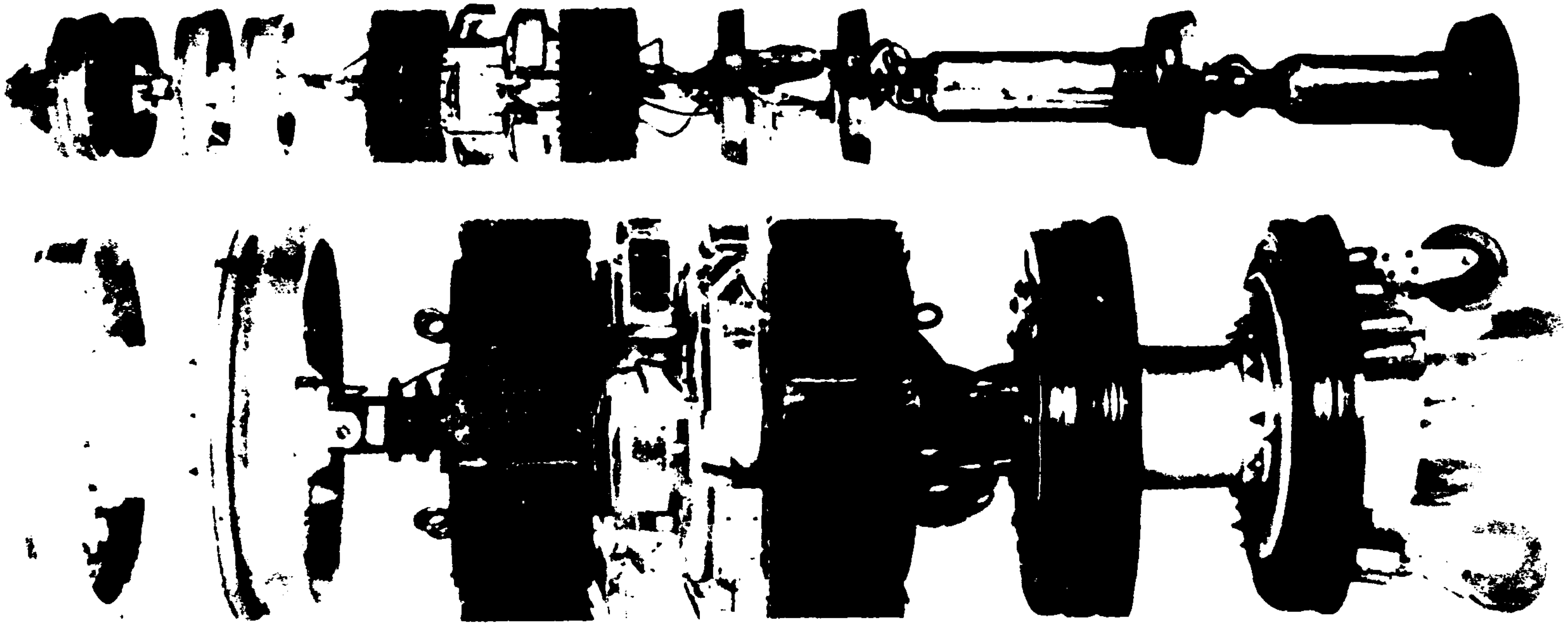


Fig. 20. AMF Tuboscope's Line-a-Log Pig. (courtesy AMF Tuboscope)

surface of the ground. Magnets are placed at closer intervals in areas suspected of serious corrosion or where the terrain is mountainous and constant speed of the tool cannot be maintained. Where necessary a special launcher and receiver trap are extended to accommodate the length of the survey pig. The pipeline is then inspected for bends with a minimum radius of three pipe diameters and corrected where necessary.

Once the above steps have been taken, a dummy tool of approximately the same size and weight as the instrumented pig is passed through the line. The travel of the dummy tool is checked at intervals to see that it is running smoothly and at the desired speed. The dummy tool is also used to determine if there are any internal obstructions which may damage or destroy the instrumented tool. The dummy tool is launched, travels, and is received using the same general procedures as those used in cleaning pigs used in cross-country crude lines.

A constant speed of throughput is desired, although minor variation in the speed will not affect the results. The small diameter tools, 15 to 41 cm, are designed to inspect and record at linear speeds of 3 to 8 km/hrs. (2 to 5 mph) average speeds, where the large diameter tools are designed to inspect and record at linear speeds of 8 to 24 km/hr. (5 to 15 mph). The difference in design speed is that the small diameter tool is restricted physically for battery capacity and has to move slower to permit the pipe wall to be saturated by magnetic flux, where the large diameter has physical room for more batteries and is capable of saturating the pipe wall with magnetic flux more rapidly. All data is stored on magnetic tape for subsequent analysis after the pig has been removed from the pipe.

The linalog survey record or log consists of several channels of information. Logs from 15 to 41 cm (6 to 16 in.) have 14 channels and logs from 46 cm (18 in.) to 91 cm (36 in.) have 29 channels, which consist of two markers, an orientation, two distance channels, and 24 survey channels. The marker channel is used to record known points, such as girth welds and magnetic reference points that were placed at exact locations prior to running the survey. The orientation channel records rotation of the instrument in the line. The distance channel records the linear progress of the tool and it does this by means of hardened steel wheels that roll on the inside surface of the pipe wall. The survey channels record irregularities encountered in the body wall of the pipe; these may include: internal or external corrosion, marker magnets, dresser couplings, girth welds, welded sleeves, patches, farm taps, gate valves, electrical connecting bonds, wrinkle bends, internal slivers, and mandrel marks.

Three general categories of corrosion are identified: light pitting (corrosion that has penetrated 15% to 30% of the nominal body-wall); moderate pitting (corrosion that has penetrated 30% to 50% of the nominal body-wall); and severe pitting (corrosion that has penetrated over 50% of the nominal body-wall). Corrosion pitting from 0 to 15 percent of the nominal wall thickness is given no classification. These classifications may be modified according to the individual requirements of the line surveyed (Swick, *ibid.*).

Vetco Pipeline Services

The "Vetcolog" pig technique is based on the principle of detecting magnetic flux leakage created by pipeline wall anomalies. Similar to the

Linalog tool, the Vetco pig is comprised of three main components: drive section; transducer (or sensor) section and instrument section. All power supplies needed to activate the pig are contained in the leading drive section. Power regulation prevents sensitivity drop off in long pipeline runs. This section is centered in the line by durable polyurethane cups which provide a sufficient seal to enable a relatively low pressure differential to push the pig down the pipeline with the product flow.

The control transducer section contains the magnetic energizing and defect sensing assemblies arranged in a manner which assures a 360-degree scanning of the pipe. The suspension concept used permits sensors to maintain constant contact with the inner surface of the pipe throughout the inspection and reduces the frictional drag of the tool. This permits uniform running speed even in rugged terrain or extreme paraffin conditions. Permanent energizing magnets are used to provide a uniform flux field concentrated at the transducers. This leaves more power available for longer runs.

The trailing instrument section contains the complete electronics system, as well as a recorder which stores the signals from each sensor. The Vetcolog pig sensitivity is independent of the rate of tool travel. It is not necessary to maintain a uniform speed throughout an inspection run as the tool will record over a broad range of speeds from 1 km per hour to the higher velocities of natural gas pipelines. A frequency modulated system provides recording and reproduction of pipeline information.

Separating the three sections are universal joints which allow the tool to negotiate pipeline bends with a radius of as little as three pipe diameters through 90 degrees. Odometer wheels are positioned on the rear of this instrument package to measure distances along the pipeline for correlating the locations of indications. For subsea pipelines an acoustic pig tracking device is also employed.

Presently Vetcolog pigs are available to conduct pipeline inspections of pipes with diameters from 20 to 76 cm (8 to 30 in.). Pigs are under development for smaller diameters as well as diameters up to 122 cm (48 in.) and larger. According to the manufacturer, employment of this pig provides information on the severity and location of the following: corrosion pitting, mechanical damage, gouges, dents, mill defects, wrinkle bends, hard spots and hydrogen blisters.

5.3 NDE EQUIPMENT DEPLOYMENT TECHNIQUES

There are three primary techniques for deployment of the NDE equipment described in section 5.1: divers, remotely operated vehicles and manned submersibles. Within these three categories, particularly the latter two, are a wide variety of configurations and functional capabilities. For example, there are over 300 ROVs of the type designated tethered, free-swimming, within which class there are 53 distinct types representative of 35 manufacturers from 11 different countries. All of these vehicles, to varying degrees, can and do offer capabilities for use in underwater NDE. Similarly, there are over 100 manned submersibles, only a small percentage of which are identical in design and functional capabilities. The following discussion, therefore, is not a detailed discussion of each and every vehicle capability, but only a general description of the major vehicle types which is keyed to their capability to conduct underwater structural NDE in Arctic waters. For a detailed description of the undersea vehicle field at large, the interested reader is referred to the work of Busby Associates, 1981.

5.3.1 Diving Capabilities

There are, like undersea vehicles, a wide variety of diving techniques and equipment, but for most NDE tasks two techniques are employed: lightweight equipment diving and bell diving.

5.3.1.a Lightweight Equipment (Air and Mixed-Gas Diving)

Lightweight commercial diving equipment can be placed into two categories. The first may be arbitrarily called facemask gear. This utilizes a full face-mask supplied by an air hose from the surface. The most commonly used full face-mask systems include a communications system and oral-nasal breathing mode if required. With full facemask equipment the diver generally wears a standard neoprene wetsuit, a dry suit or a hot-water suit.

The second category is helmet equipment, which employs a lightweight fiberglass or metal helmet which is functionally similar to a hard hat. The helmet also incorporates two-way communications, as does almost all surface-supplied commercial diving equipment. Both systems include weight belts and boots or swim fins.

The advantages of lightweight helmet gear are that it offers an unlimited air supply, good communications, good mobility and minimum physical restrictions. Helmet gear also provides head protection and, when used with a dry suit, offers buoyancy control and effective protection in cold water.

The necessary support equipment for surface-supplied lightweight full-facemask and helmet gear includes an air compressor and volume tank, communications equipment, a diving stage and, if the job is deeper than 30 meters or outside the no-decompression limits, a decompression chamber. A Class II open diving bell often replaces the diving stage on deeper surface-supplied air diving jobs as a diver transport method. The open bell can be used as a bottom refuge in case of diver equipment malfunction underwater.

Air diving with surface-supplied lightweight equipment is usually limited to 60 to 70 m because of the possibility of nitrogen narcosis.

Mixed-gas diving equipment is essentially the same as air diving gear, except that the most common systems incorporate a means of partially recirculating the breathing gas in order to avoid exhausting all of the pre-mixed gas into the water. Mixed-gas is also sometimes used with full facemask equipment operated in the "demand" breathing mode.

5.3.1.b Bell Diving Systems

There are hundreds of diving systems in operation. These range in capability from open diving bells for brief excursions to 30 or 40 m, to pressurized saturation diving systems which can support divers at depths in excess of 500 m for weeks at a time. As a general rule of thumb, bell systems are desirable at depths in excess of about 70 m.

A deep saturation diving system is generally composed of the following subsystems: Submersible Decompression Chamber (SDC) or diving bell; Deck Decompression Chamber (DDC); Living Chamber (LC); Entrance Lock (EL): Control Van (CV); SDC handling system, gas supply systems, life support system, sanitary system, diving equipment/heating system, gas analysis system and auxiliary equipment and spare parts/tools. There are more than 23 manufacturers of SDCs, DDCs, LCs, ELs and twice that number who manufacture the hardware and electrical components critical to each system. The following characteristics therefore cover a very broad field in which averages pertaining to equipment dimensions and mass are virtually meaningless. (Taylor Diving and Salvage Company, for example, has 21 diving systems all of which vary in lesser and greater degree one to the other.)

Operating Depth:	to 500 m
Personnel Capacity:	SDC: 2 to 3 DDC: 2 to 15
Dimensions:	SDC: Spheres: 1.5 to 2.4 m (LxWxH) Cylinders: 2.1 to 3.9 m x 1.5 to 2.0 m x 1.5 to 2.0 m (LxWxH) DDC: 3.8 to 10.4 m x 1.5 to 2.5 m x 1.5 to 2.5 m (LxWxH)
Weight in Air:	SDC: 3 to 16 tonnes DDC: 2.7 to 21.7 tonnes Total System: 21 to 69 tonnes
Launch/Retrieval Technique:	U-Frame: Traveling Boom (over the side or within a moon pool or center well)
Surface-Supplied:	Breathing gasses, communications, electrical power, hot water (via umbilical)
Number of Units Operating:	In excess of 400

In regards to Arctic diving operations, none of the ocean water properties delineated in section 1.2 would be inherently prohibitive to employing divers underice using the appropriate presently-available commercial equipment. Underice diving has been conducted safely and successfully for over a decade.

5.3.2 Remotely Operated Vehicles

There are four types of ROVs: tethered, free-swimming; towed; bottom-crawling or structurally-reliant, and autonomous. From an NDE point of view the first type, tethered, free-swimming vehicles, are used almost exclusively. The last type, autonomous vehicles, are, at this point, mainly developmental, but they do indicate potential for future NDE employment. Towed vehicles are almost exclusively used for surveying and mapping; bottom crawling and structurally reliant vehicles are almost exclusively used for cable and pipeline trenching, these two types will not be further discussed.

5.3.2.a Tethered, Free-Swimming

Carries CCTV and is capable of maneuvering in three dimensions. Power is supplied from the surface via an umbilical cable. Designed primarily for mid-water operations. Dives positively buoyant and relies on vertical thrusters to remain submerged. Manipulative capability available. An ROV system consists of the following components: control/display console (for controlling the vehicle, monitoring its performance and displaying data) a vehicle launch/retrieval system, an umbilical cable (providing power and control functions to the vehicle and telemetering data to the surface), an optional vehicle cage or launcher (to protect the vehicle during launch/retrieval and to keep the main umbilical cable taut while the vehicle operates from a smaller diameter, shorter cable), the vehicle itself and a power supply (derived either from the support platform's power or a dedicated generator). Capabilities and characteristics of the industrially-available vehicles are as follows:

Operating depth	:	30 to 3,000 m
		Average 1,000 m
Dimensions (length)	:	0.5 to 5.0 m
		Average 1.62 m
Vehicle Weight in Air	:	32 to 5,500 kg
		Average 607 kg
Vehicles employing Subsea Cages/Launchers	:	31% Weight of launchers 80 to 2,495kg
		Average weight 222 kg
Operating Crew	:	1 to 10
		Average number: 3
Electric Power Source	:	93% of all vehicles derive their power from a surface generator with an umbilical. The remainder use

onboard batteries. Voltages used range from 115 to 1000 VAC. The majority of vehicles use 120, 440 or or 220/440 VAC. Power requirements range from 2.5 to 2000 KW; 30 KW is average.

Propulsion: Three motions are attainable by 85 percent of ROVs: thrust (forward/reverse); heave (up/down vertically) and sidle or sway (left/right translational). These motions are provided generally by a combination of individual forward, vertical and lateral thrusters or by a combination of forward and vertical/transverse thrusters.

Manipulators: Manipulators are standard equipment on 34 percent of the operating vehicles. Of these, 73 percent carry only one manipulator; the remainder carry two. Manipulator degrees-of-freedom or functions range from 2 to 7 with 3 to 5 functions being most common.

Speed: Ranges from 1.0 to 7.0 knots. Average - 2.3 knots.

Instrumentation: Standard equipment consists of closed-circuit television (CCTV), one or several lights for TV viewing, a depth sensor and a magnetic compass or, less frequently, gyrocompass. A wide array of navigational and work instrumentation is carried singularly or in combination depending upon the vehicle dimensions, power, and payload.

Number of Vehicles: Over 300

5.3.2.b Autonomous Vehicles

Vehicles of this type operate independently of an umbilical cable and carry battery power onboard. Some are pre-programmed to carry out a particular task, such as search, mid-water measurements or under-ice profiling, while others can be controlled in course and depth to collect a variety of oceanographic research and survey data. There are some 13 of these vehicles, three are operational and the remainder are under development. Of the 13 vehicles two have specific application to underwater NDE, these are the vehicles EAVE WEST and EAVE EAST, being developed by the Naval Ocean Systems Center, San Diego and the University of New Hampshire's Marine Systems Engineering Laboratory, respectively. Both developments are funded by the Dept. of the Interior's Minerals Management Service. Since both vehicles are developmental, they are discussed, more appropriately, in section 7.2.3.a.

5.3.3 Manned Submersibles

Four types of vehicles fall into this category: 1-ATM, free-swimming vehicles, Observation/Work bells, Lockout vehicles and Atmospheric Diving Suits.

5.3.3.a One-Atmosphere, Free-swimming Vehicles

This class of manned submersible constitutes the more or less "conventional" vehicle. They support their occupants at one-atmosphere pressure and are either self-powered by batteries or receive power from a surface-connected umbilical cable. Maneuverability is obtainable in the x, y and z axes by control of onboard thrusters, hence, the term "free-swimming". The following data defines the boundary capabilities of commercially available vehicles in this class:

Operating Depth	:	150 to 3000 m
Crew	:	1 to 10
Weight in Air	:	1.0 to 168 tonnes
Payload	:	200 to 4,536kg
Electrical Power	:	4.5 to 740 KWH (Unlimited when using surface umbilical)
Life Support Duration	:	48 man-hours to 89 man days
Maneuverability	:	3-dimensional
Manipulators	:	1 to 3
Number of Vehicles	:	62

5.3.3.b Observation/Work Bells

Occupants at one-atmosphere pressure. Power derived from batteries or via umbilical cable. Designed for finely-controlled maneuverability in the x-y axes, limited self-maneuvering capability in the vertical (z) axis. Always operates with tether to the surface. Capabilities and characteristics of commercially available vehicles:

Operating Depth	:	300 to 1,000 m
Crew	:	2 to 3
Weight in Air	:	3.5 to 9.5 tonnes
Payload	:	250 to 400kg
Electrical Power	:	24 to 29.3 KWH. Unlimited with surface umbilical
Life Support Duration	:	96 to 478 man-hours
Maneuverability	:	3-dimensional
Manipulators	:	1 to 2 (one for grasping structure; one to work)
Number of Vehicles	:	14

5.3.3.c Lockout Vehicles

Submersible configured into two sections (generally interconnected), one section is at 1-atmosphere pressure and supports pilot and observer, the second section can be pressurized to ambient pressure and serves to lockout diver and support diver/tender and supervisor. Vehicle is free-swimming, electrical power is supplied either by onboard power source or surface-connected umbilical. Maneuverability is obtainable in the x, y, and z axis by control of onboard thrusters. Life support, diver heating, and breathing gasses carried onboard. Capabilities and characteristics of commercially available vehicles:

Operating Depth	:	259 to 488 m
Diver Lockout Depth (max)	:	488m
Crew	:	1 pilot, observer, 1 dive supervisor and 4 divers
Weight in Air	:	8.1 to 23 tonnes
Payload	:	150 to 1,497kg
Electrical Power	:	32 to 126 kHz (batteries)
Life Support Duration	:	24 hours (using closed-cycle diesel engine), unlimited using surface-connected umbilical
Maneuverability	:	3-dimensional
Manipulators	:	1 to 3
Number of Vehicles	:	13

5.3.3.d Atmospheric Diving Suits

One person capacity. Occupant at one-atmosphere pressure. Powered by operator or by surface-connected umbilical. Two dimensional to three dimensional maneuverability, anthropomorphic configuration; always operates from surface-connected cable. Capabilities and characteristics of commercially-available vehicles:

Operating Depth	:	457 to 610m
Crew	:	1
Weight in Air	:	245 to 1,089kg
Payload	:	10 to 27kg
Electrical Power	:	Unlimited using surface-connected umbilical

Life Support Duration	:	20 to 80 man-hours
Maneuverability	:	x-y axes with manually-powered vehicles; x, y, z axis with surface-powered vehicles
Manipulators	:	2
Number of Vehicles	:	28

The frequency of application and the relative suitability of the deployment techniques described above to employ the various NDE tools is shown in Table Several aspects of this Table should be clarified. The diver becomes non-competitive in depths exceeding 250 to 300 m. Although working dives in excess of 400 m have been performed, they are not conducted routinely owing to the great complexity and high cost. Consequently, as a routine inspection technique, diving is usually restricted to shallower depths. For Arctic application, however, 300 m will satisfy present and foreseeable near future requirements. It should be emphasized that the relative utilization frequency of various deployment techniques reflects what is the present degree of utilization; not the potential degree. There are a variety of industrial efforts now underway aimed at using ROVs for many of the tasks which the diver now performs. Undoubtedly, when Arctic oil and gas development has reached the production stage a wider range of inspection capabilities will be available. Atmospheric Diving Suits and Observation/Work Bells are used primarily in the exploration and development phases of offshore oil and gas activities. Their design and capabilities are aimed at providing a high degree of manipulation and maneuvering within a localized work site, rather than providing large instrument payload or long-ranging transiting, for this reason they have not yet found extensive application in pipeline inspection. The bell diver, likewise, is not extensively used for routine pipeline inspection.

Concerning present and previous application of these deployment techniques in Arctic waters, the diver has been used almost exclusively. Application of manned submersibles and ROVs has been infrequent and almost always for scientific research projects. The ADS (i.e., JIM and WASP) have found occasional drilling support employment, and previous efforts with autonomous vehicles have all been experimental. As far as can be learned, pipeline pigging has not been performed in the Arctic, although there are unpublished reports of their utilization in sub-Arctic regions such as the Cook Inlet off southern Alaska.

Table 7
NDE EQUIPMENT DEPLOYMENT CAPABILITIES

NDE Task/Equipment	Diver	ROV	1-ata Sub	ADS	O/W Bell
Structures					
Visual Inspection	F	F	L	L	L
CCTV Inspection	F	F	L	L	L
Still Photography	F	F	L	L	L
Cleaning	F	L	L	L	L
c-p monitoring:					
Remote	N	N	N	N	N
Direct	F	F	L	L	L
MPI	F	N	N	P	N
Magneto-Marine	F	P	P	P	P
Fe-Depth	F	P	P	P	P
Ultrasonics:					
Thickness	F	L	L	L	L
Flaw Detection	F	P	P	P	P
Radiography	F	P	P	P	P
Tomography	F	P	P	P	P
Pipelines					
Visual Inspection	L	F	F	L	L
CCTV Inspection	L	F	F	L	L
Still Photography	L	F	F	L	L
Coating Removal	F	N	N	P	P
c-p monitoring:					
Remote	N	F	F	N	N
Direct	L	F	F	L	L
MPI	F	N	N	P	N
Ultrasonics:					
Thickness	L	L	L	L	L
Flaw Detection	F	P	P	P	P
Radiography	F	N	N	N	N

F Frequent Application
L Limited Application
N No Application at present
P Potential Application

6.0 UNDERWATER NDE PERFORMANCE AND LIMITATIONS

At present the only reported form of Arctic underwater NDE has been performed by divers and consists of visual and TV inspection, photographic documentation, and magnetic particle inspection of ships' hulls. A form of underwater NDE was performed in 1981 by Patterson, et al (1982) wherein a side scan sonar was employed from a surface ship to assess the integrity of sand bags providing slope protection for an artificial island in the Beaufort Sea. This work was performed during the ice-free season. The NDE performance baseline in the Arctic is, therefore, very limited in both tenure and scope. Nonetheless, the extensive experience gained in other environments, such as the North Sea, can be used as a yardstick to measure the potential for underwater NDE success in Arctic regions. This section relates these experiences and extrapolates them to examine potential future underice problems of structure and pipeline NDE.

Basically, underwater NDE limitations can be placed into three categories: 1) data accuracy and significance; 2) NDE equipment performance and 3) the equipment deployment techniques (i.e., diver, ROV, manned submersible). The Arctic poses a fourth category: ice, which in many respects can be the major overriding limitation on Arctic underwater NDE efforts.

6.1 OVERALL EQUIPMENT/PERSONNEL PERFORMANCE

Since the 1976 instigation of UK governmental inspection requirements for structures, the North Sea has become the test tank for virtually every type NDE device and technique available. Many devices, while conceptually or theoretically deemed suitable for its rigorous environment, fell far short of their promise under actual field conditions. Some problems, such as marine fouling and access to the structure, almost immediately loomed as critical as the inspection device or technique itself. Faulds (1982), for example, cites preparatory cleaning of a structure as accounting for upwards of 90 percent of the time involved in conducting the actual examination. The short North Sea weather window, combined with activities on and about the platform, severely limited the duration of time within which the examiner could realistically work. In this respect, Smeadley of Lloyds Register of Shipping (1979), related that because of the short weather window and because platform activities necessitated downtime of about 150 percent in excess of that employed for useful underwater work, the UK Department of Energy amended their Guidance on Major Survey Requirements from a minimum of 10 percent of all critical welded joints to a schedule agreed to between the platform owner and the Certifying Authority.

In order to separate reality from wishful thinking among the growing inventory of commercially-available NDE techniques, Occidental Petroleum commissioned Brown and Root to conduct a test of NDE techniques on a submerged mock structure in which defects were intentionally incorporated in the nodes. The first series of tests, designed to weed out those devices which had no foreseeable applicability, was conducted in the protected waters of Peterhead Harbor, Scotland, in depths of 7 m. The second series of tests were conducted offshore in 145 m water depths. The results were disappointing, in that, although some devices did perform adequately, the general concensus was that commercially-available equipment was unsuitable for underwater flaw detection (Hayward, 1978).

Dr. S. Fjeld (1982) of Det Norske Veritas reached somewhat similar conclusions based on nine years of inspecting a total of 11 North Sea offshore concrete structures. Commenting on the dubious results and limited applications of available NDE techniques, Fjeld concluded that from a practical and cost point of view it is fair to assume that all sources of damage to concrete structures will be observed by a close visual inspection before they reach an extent jeopardizing the structure. Conditions such as, overloading, rebar corrosion, deterioration and sulphate attack, would become visible on the exterior through excessive cracking; surface staining, cracking and spalling, and loose concrete vulnerable to scraping and crumbling of the surface, respectively.

From a variety of sources, the following comments pertain to the underwater NDE field at large and have been extracted to identify the overall limitations and problems in current equipment and personnel.

-Cleaning preparatory to weld inspection accounts for some 90 percent of the inspection procedure (Faulds, 1982).
-The cleaning requirements for mpi, ultrasonics and radiography necessitate removal of protective coatings (Poole, 1980).
-Localized grinding of indications for further examination, if performed improperly, may leave additional stress raisers which may lead to eventual fatigue failure. (Collier, 1981)
-Improper removal of coatings can sometimes leave serious mechanical gouges having metallurgical significance. (ibid.)
-Commercially available equipment is unsuitable for flaw detection even in shallow protected waters, the problem becomes more severe in deep, unprotected waters. (Hayward, 1978)
-Commercial NDE methods are, for the most part, not only unable to find defects, but when they are found they are not capable of sizing the defect in the critical through-the-thickness dimension. (Webborn, 1980)
-Current methods are, in the main, adapted from on-land equipment; they often ignore the operational limitations of the diver or submersible. (Poole, 1980)
-NDE has progressed from on-land testing and the precepts developed have been directly applied to the subsea environment, but they have proved irrelevant. (Allen, 1980)
-All problems stem directly from the widespread involvement of non-expert NDT personnel on all levels. (ibid.)
-Too much dependency and responsibility on the diver for delicate manipulation and judgment. (Poole, 1980)
-Manipulation of probes may become difficult and the accuracy of the interpretation may subsequently decrease with time spent underwater. (Hayward, 1978)
-NDE training of divers is sporadic, leading to a critical shortage of skilled, deep-diving NDE technicians. (Offshore Services & Technology 1980)
-Equipment is too heavy, bulky and unwieldy. (Hayward, 1978)
-Much of the equipment is depth sensitive. (ibid.)
-NDT has so far not been used with success on offshore concrete platforms underwater. (Fjeld, 1982)

6.2 NDE EQUIPMENT LIMITATIONS

The foregoing presented the overall limitations to current NDE techniques, the following identifies limitations as reported for specific devices and capabilities. Some NDE techniques are not discussed since there has been no reported evaluations of the particular device or because it is in the developmental stage, this is the case with the Magneto-Marine method, tomography, FUNDIT and the Ultrasonic Torch.

6.2.1 Visual Inspection

- -Visibility can be virtually nil (Poole, 1980)
- -Only relatively large defects can be seen, cannot observe tight surface cracks.
- -Assessment depends on diver's training, experience and psychological condition.
- -No permanent record
- -Protective coating must be removed to observe small defects.

6.2.2 Television Inspection

- -Visibility variable, affects quality of record
- -Only fairly large defects can be seen, cannot record fine detail such as hairline cracks
- -A 3-dimensional view is lacking
- -Color fidelity is questionable
- -Resolution is inadequate

6.2.3 Photographic Inspection

- -Visibility variable
- -Extensive training and experience required for high quality results
- -Results not presented in real-time

6.2.4 Magnetic Particle Inspection

-No one knows why this technique works nor under what conditions it works best. (Poole, 1980)

-Can detect tight, surface-breaking cracks only if the surface is dressed, magnetic field is correctly aligned and sufficiently intense and if a high standard of illumination is used with background paint. (Brown and Bennett, 1981)

<u>Using permanent magnets</u> (King and Lumb, 1980)

-To obtain the necessary flux field permanent magnets would need to be so powerful as to be not maneuverable by hand, if electro-magnetics are used the advantage of convenience is lost.

-The magnetic field is not deliberately variable to defined values though it is easily inadvertently varied such as to negate the test.

-The field strength is not measurable

-The method is time-consuming as only a small area of the structure can be examined with only one magnet condition.

Using Contract Prods (ibid.)

-If the weld is not straight at the nodes or in fillet welded lugs and reinforcing pads, then at some locations the field strength will be significantly less than that anticipated by applying amps per unit distance of prod separation criteria. The problem can be overcome by specifying exact locations for the prods, but in the context of offshore application it is not reasonable to expect rigid adherence to locations.

-The prods pass high current at low voltage. Arcing, causing hardened zones and in extreme cases copper contamination, is inevitable. Such zones potentially initiate cracks, and if contaminated, anodic corrosion. Current will only flow if the contact resistence is low. This requires a firm even pressure to be maintained on the prods and a clean (virtually bare metal) surface.

-Maintaining even prod pressure is extremely difficult underwater and there is no obvious solution to the problem. In currents it is difficult for a diver to maintain station, let alone press prods against a structure. In turbulent regions such as the splash zone, the problem is even more severe. Two NDT technician/divers are required, one for prodding while the other applies the ink. It is necessary for them have simultaneous access to that part of the weld being examined. On some parts of a structure, particularly at nodes, such access is at a premium. In the splash zone the procedure is virtually impossible.

-Cannot determine depth severity of defect (Hayward, 1978)

-Access for conventional mpi is restricted when investigating welds in angles less than 60 degrees. (ibid.)

-Utilizing magnetic rubber instead of magnetic particles produces marginally better results with a hard copy, but the rubber takes "fore " to cure in cold water. (Mittleman and Wyman, 1980)

-Can only detect discontinuities that are open to the surface (Collier and Goldberg, 1981)

-Experience and skill in interpreting the significance of crack patterns is important. (ibid.)

-Detection success of fatigue cracks less than 20 to 30 mm length is low. (Faulds, 1982)

-Protective coating must be removed.

5.2.5 Ultrasonic Inspection

-Repeatability unreliable (According to Faulds, 1982, the hull thickness of one of Shell UK's structures reportedly increased year by year over a three-year period as measured by ultrasonics.)

-Many UT devices require two hands for operation, the diver needs at least one free hand to hold himself in place.

-For fault detection an inordinately high level of operator skill and interpretation is required to position and locate probes and interpret the results.

-Only suited for detecting defects within the welds to somewhere greater than 5 mm below the surface, therefore is limited to sizing defects found by other methods such as mpi.

-Fault detection does not normally provide a permanent record. (Poole, 1982)

-Fault detection is a slow procedure under the best of conditions. (Poole, 1982)

-Underwater results are not acceptable for concrete structure inspection. (Fjeld, 1982)

6.2.6 Radiography

-Access to both sides of a structure is required, this is frequently not possible.

-Joint or node geometry may preclude use of radiographic techniques.

6.3 Deployment Technique Limitations

The following discussion concentrates primarily on the limitations which have been identified for each of the three deployment techniques in the pursuit of NDE. Intrinsically, a discussion of this nature will be critical of the various techniques. It should, therefore, be noted that, in spite of their shortcomings, they have been successfully conducting underwater NDE under extremely hostile conditions and at great depths for the past several years. Further, the discussion tends to compare one technique against the other. This is virtually unavoidable and unfortunate. Because no one technique is better than another under all the wide range of environmental and operational variabilities encountered. In this respect it is important to observe that all the major underwater service companies have in-house or can provide the capability of offering all three techniques. The selection is dependent upon which one is the most suitable for the task.

6.3.1 Diving

The diver in offshore NDE is the most widely used and successful technique now available. While his wide range of capabilities is acknowledged and appreciated, almost everyone would like to replace him. In certain instances, as are identified in the following chapter, his replacement is being pursued, but for now and in the foreseeable future he will continue to play an integral role in underwater NDE. The following comments identify the weaknesses and strengths of the diver which have been observed in the North Sea and elsewhere in underwater inspection.

Personnel Safety

It would be laboring the obvious to dwell upon the vulnerability of the diver in regards to his working environment. Of the three techniques used to deploy NDE tools and devices, ambient pressure diving introduces the greatest potential for jeopardizing human life. No one in industry will argue against this basic fact of life, but, on the other hand, there has been no reported diving fatality in the pursuit of NDE to date.

Operating Depth

Of the three techniques, diving is the most limited in regards to the depth in which it can be carried out. While Comex and the French Navy demonstrated in the early seventies that safe and successful working saturation dives can be carried out in depths of 501 m., most routine inspection diving does not progress much beyond 200 m., and oftimes much less. Significantly, for foreseeable Arctic depths this limitation is not prohibitive.

Personal Judgment

The judgment of an individual underwater under field conditions is speculative. There is no doubt that some part of his concentration is frequently, if not near-continually, upon the subject of his survival. How thoroughly and how comprehensively he applies his thoughts to the structure's or pipeline's integrity has not been quantified to any degree of reliability. Probably the practice of "one hand for yourself and one hand for the ship" which seamen apply during high seas, can be applied to the division of concentration the diver follows.

Engineering Expertise

Since most divers are not engineers, and--in particularly--are not formally educated in structural mechanics, their judgment regarding the state of a structure or the criticality of a defect is limited. Several commercial training centers have been established in Europe and the U.S. which offer two and three week courses designed to instruct the diver in the use of various NDE tools. But none of these schools purport to graduate an engineer qualified to interpret the results of his survey or the implications of the results to structure integrity. Television and photography helps to overcome this inadequacy by permitting a qualified surveyor to view the same scene as the diver and to direct him in the pursuit of his task. Det Norske Veritas has trained some number of its qualified NDE engineers to dive and conduct an inspection. While this procedure theoretically introduces uniformity of terminology and professional expertise, the engineer/diver is no less concerned about his survival than any other diver, and the judgment factor must once again be confronted. Moreover, of the more than 6,000 commercial divers at work offshore, the percentage of this group which are trained and educated engineers is virtually negligible.

Access to Nodes and Structure Interior

There are various legal and self-imposed requirements regarding the distance to which a diver on an umbilical can penetrate a structure. Providing the requirements--which involve support vessel mooring and positioning and other operational considerations--are satisfied, there is no offshore oil or gas structure presently in operation which the diver cannot safely and effectively penetrate for NDE. In certain nodes where the angles between members are 30 degrees

and less, diving is the only technique which can be effectively employed to clean and inspect a weldment.

Payload

All current devices for conducting magnetic inspections, c-p monitoring, ultrasonics, radiography, photographic and TV documentation and preparatory cleaning are designed for diver application. Consequently, they are within his payload ability to handle and employ from a bell or from a stage. The procedural techniques to deploy these tools by the diver are almost all designed for utilization on a fixed structure. In this respect several of the larger components, which, for example, are incorporated in mpi devices, are lowered by winch to a location and depth convenient for the diver and adjacent to the work site and held on location by a surface-connected cable. As a freely-roving platform carrying an array of NDE devices and support equipment the diver is limited, in that, his payload carrying capacity is supplied by the bell or stage from which he is operating and limited in range to the length of his tether.

Transitting

The commercial offshore diver is relatively limited in the distances he can travel laterally while conducting an inspection. Diving bells and stages are not designed to follow the diver as he makes his way along a pipeline or cable. They are, instead, designed to support the diver at a single spot while permitting him to make excursions from this spot to the limit of his tether . While it is conceivable that a bell can be moved and the support vessel remoored or station-keep from site-to-site and provide a support base for diver inspection along pipelines, it is not a cost-effective solution. In certain instances and in shallow waters (10 to 15 m) a practice known as live-boating has been pursued. Live-boating entails the surface-support ship following the diver while he walks (swimming is practically impossible since his tether must be pulled by him) along a pipeline conducting the inspection. A second form of live-boating has been conducted by lock-out submersibles whereby the vehicle follows the locked-out diver while providing him life support, heating, lighting, instruments and power. This form of live-boating can significantly increase the diver's transitting range at depths up to 200 m and greater.

Availability

There are an adequate number of diving systems and divers to conduct all present and foreseeable inspection requirements. The systems are sufficiently transportable and provide adequate flexibility to meet foreseeable Arctic requirements.

Manipulation

The human hand and brain is the yardstick by which all mechanical manipulators are measured. In this respect the diver has no present or foreseeable replacement.

Surface Support Requirements

Support requirements for the diver in saturation are extensive. Earls (1979) observed that the amount of surface support equipment and consummables

required to support a saturation diving job can total over 100 tons. (As a comparison, Earls stated that in the case of an ADS it is usually 12 tons.) During inspection of BP Petroleum Development's structures in the Forties Field, Freeman (1980) reported that the conventional bell system employed was supported by a converted fish factory vessel fitted with a 4-point mooring system, a computer-controlled dynamic positioning system, a built-in saturation system capable of supporting eight persons, a bell launch/retrieval system operating through an aerated moonpool and a complement of 21 diving operators, 5 inspection staff for a 24-hour operating basis. Total ship's complement was 60. Obviously, when, for example, mpi is being conducted in the splash zone where saturation diving is not required the surface support facilities are significantly reduced.

Station-Keeping

Station-keeping in this respect refers to the ability of the diver and his support ship to remain at the work site in the presence of currents (for the diver) and wind and currents for the support ship. Except in the case where the possibility of gale force winds occurring may force the support platform to abort the dive and curtail operations, station-keeping limitations are generally imposed by the diver. A survey of eight major diving companies (Busby Associates, 1980) revealed that the diver was limited to a maximum current less than 3 knots and generally 1.5 knots or less. The diver support platforms could maintain station in sea states from 5 to 7 using either a 3 to 4 point moor and/or a dynamic positioning system. The diver can, obviously, by merely holding on to some part of the structure maintain station in currents higher than 1.5 knots, but he only does this by sacrificing his ability to manipulate. Recent developments in ROV technology have introduced a diver-assist vehicle called DAVID (Marsland and Marschwer, 1982) which is designed to clamp onto a structure and provide, among other functions, a stable platform upon which the diver can work. Such devices may increase the diver's ability to work in high current areas.

Dive Duration/Power

No limitation can be foreseen in this area since divers can and have been safely and efficiently supported for periods up to several weeks, more than adequate to conduct NDE of an individual structure. Since electrical power is derived from a surface generator via an umbilical, power is essentially unlimited in duration.

Reliability

Herein the term reliability refers to the operational performance of the deployment technique while underwater. It does not indicate the reliability of the data collected, but is a measure of the percentage of time which the vehicle or diver/diving system is capable of operating once it has been deployed. From this vantage the diver has demonstrated the highest degree of reliability. A comparative study of divers, submersibles and ROVs in inspection tasks conducted by Freeman, (op. cit.), showed the following percentages in performance:

	Dive Bell	Submersible	ROV
Underwater Time	39.6%	28.0%	25.9%
System Maintenance and Operational Delays	15.4%	59.6%	62.9%
Unavoidable Downtime	45.0%	12.4%	11.2%

The above reflects only one isolated example of the three techniques' reliability and is skewed, perhaps unreasonably, toward the diving system since the submersible was one of greater complexity than most and the ROV was newly developed. (The submersible used was a lockout vehicle and the ROV had virtually no previous field experience.) Nonetheless, the reliability (or downtime due to maintenance and operational delays) of the diving system is fairly representative for this type deployment technqùe. Since saturation diving is the most complex form of offshore commercial diving, it is safe to assume that the reliability will improve when the less complicated, non-saturation diving systems are used.

6.3.2 Manned Submersibles

The wide variety of design and capabilities of manned submersibles precludes addressing their limitations overall. There is a great degree of specialization represented by each of the types described in section 5.3.3 and more specialization within the types themselves. For example, the ADS JIM was designed to provide a high degree of manipulative dexterity, not to range freely about the bottom conducting surveys or pipeline inspection tasks as would a 1-atmosphere, untethered submersible. WASP, a follow-on ADS to JIM, provides equal manipulative dexterity, and also offers the capability of mid-water, closely controlled maneuverability. There is, consequently, an almost infinite variety of one or several unique capabilities contained within each of the more than 100 manned submersibles available for inspection work, for this reason the perils of generalizing are emphasized.

Personnel Safety

If the advent of the bathyscaph FNRS-2 in 1948 can be assumed as the beginning of contemporary submersible development, then over the 34-year history of submersible utilization a total of six fatalities have occurred. In light of this record submersibles can be considered as being safe. Whereas the ambient pressure diver can be subject to non-fatal, but disabling accidents, the submersible occupant generally follows the all or none law. In that, he emerges alive and well, or dead. Relative comparisons as to the safety of submersibles vs. diving are meaningless since the number of hours logged underwater by industrial divers so far exceeds the number of hours logged by submersibles that there is no realistic basis of comparison. Submersible diving is not, however, without its share of potentially dangerous incidents, which occur with regularity in the offshore industry, particularly in work which involves maneuvering in and about structures and hardware. In such work entanglement of umbilicals and entrapment of the vehicle has held the occupants underwater for unscheduled periods ranging from hours to days, but with no reported fatalities since a 1976 occurrence during an indoctrination dive.

Depth

There are no current offshore oil and gas activities taking place in water depths inaccessible to today's inventory of manned submersibles. The relatively

shallow depths foreseeable in this decades Arctic operations are well within the depth range of present and planned vehicles.

Personal Judgment

All but one type of submersible, the ADS, has room to accommodate both the vehicle operator and an observer. In such vehicles the observer can be a qualified NDE surveyor and requires no more than the physical ability to crawl into and out of the vehicle. Consequently, the personal judgment of an unqualified or minimally trained observer is avoided. Nonetheless, there is still a psychological factor working to the detriment of the observer since he, like the diver, is quite aware of being underwater and, to some degree, this awareness makes inroads on his ability to devote his full time to uninterrupted, concentrated technical observations. There is some degree of reassurance, however, gained from the company of another human. The ADS operator can be an engineer trained and qualified in its operation, and he may, like the DnV engineer/diver, be an ADS pilot/engineer. In this respect the personal judgment is out of the hands of the unqualified, but the stress factor is ever present. Sheader (1980), in describing his operational experiences with the one-man MANTIS vehicle likens the stress as being analogous to that of the diver and closely connected to the type of work involved. Highest stress being present when working about structures in close confines and poor visibility.

Engineering Expertise

As noted above, all classes of submersibles, except the ADS, can transport individuals of whatever background is necessary to the inspection site in a dry, shirt-sleeve environment with a great measure of physical comfort and with no diving training of any type required. In the lockout type submersible the inspector can direct and supervise the diver by literally looking over his shoulder as the NDE is being conducted.

Access to Nodes and Structures

This is an area where generalizations are particularly difficult to make. Particularly so when considering the lockout vehicle which can, at a suitable location and when adequately ballasted or secured to the structure, deploy and support the diver as does a bell system. In such circumstances the manned submersible has as much access to the structure's interior and to nodes or joints as does the diver. Disregarding the lockout vehicle permits a few overall observations. Virtually all submersibles incorporate some degree of near-panoramic viewing in the bow in the form of an acrylic plastic dome. This permits the occupants to observe or inspect a member from distances as close as a few centimeters, in some instances the bow dome can be in contact with the structure, although the prudent operator may not elect to exercise this option. Entering the structure to inspect the interior is dependent upon the prevailing current and visibility, the extent to which the internal members and nodes are marked (for navigation), the dimensions and mass of the vehicle, its station-keeping capabilities, whether or not the vehicle is trailing an umbilical, the extent and nature of potential entangling debris and, of course, the geometry of the structure itself. The ADS class vehicle and the one-man submersible is particularly vulnerable to entanglement inside a structure owing to their umbilicals. (These can be jettisoned in the event of entanglement, but it is

a last resort effort which the operator would not routinely plan as part of the operational scenario.) Present developments with the WASP ADS are aimed at producing a tether management system or garage which will hold the cable taut at the depth of operation and permit the vehicle to enter a structure with the trailing umbilical in a horizontal plane. (Hampson, 1980) In substance, the degree of access to a structure's interior is accompanied by so many variable factors that judgments regarding this capability must be made on a case-by-case, vehicle-by-vehicle basis incorporating current and visibility considerations.

Access to nodes entails the same considerations as access to the interior, ... additional, overriding consideration: the angle between members. It w... be physically impossible for any present submersible to position itself nearer than a meter directly above the weldment being inspected in the node shown in Fig. 12. On some structures upwards of five or more members may join at a common point which would prove exceedingly difficult for a submersible of even modest size to penetrate and examine visually in fine detail.

Payload

The capability for carrying instrumentation or tools beyond those necessary for the vehicle's routine operations varies widely. The ADS class has the least payload: 10 to 27 kg. The remaining vehicles have payloads which range from 150 kg to over 4500 kg, this is more than adequate to carry a full suite of NDE equipment and devices. This payload carrying capability permits most submersibles to conduct wide-ranging, relatively long-distance inspections of pipelines and cables. The ADS-type vehicle, because of its cable and the drag it introduces is less capable of conducting inspections requiring long lateral transiting. While the ADS payload can accommodate at least one, and perhaps two of the current NDE devices, their attachment to the vehicle introduces other problems. Allen (1980) reported that the current industry practice of adding on to the suits' external framework existing NDE equipment has produced significant degradation of ADS hydrodynamics through increased drag resulting from the attached bulky objects. This is quite critical, according to Allen, in a situation where thruster power is already at a premium.

Transitting

The 1-atmosphere, untethered vehicles and lockout vehicles are designed for long-range transits which are limited primarily by electrical (battery) power. This transitting ability (upwards of 80 km/day in one instance, but more generally 10 to 15 km/dive) allows inspection and NDE of pipelines irrespective of the surface support ship position. The payloads of such vehicles also allow a variety of examinations to be conducted without returning to the surface for a different device. Observation/Work Bells and ADS's are constrained in the ability to conduct long range transits owing to the restrictions brought about by umbilical cable drag. Much like the diving bell or stage, these vehicles can perform long-range inspections, but the logistics of moving from point-to-point do not permit an economical solution in most instances. Thruster-propelled ADS's are better equipped to perform long-range inspections, and with the inclusion of a cable management system such as noted above for WASP, they may find such tasks economically competitive with other manned submersibles and ROVs.

Availability

There is no shortage of manned submersibles to meet foreseeable Arctic inspection requirements. All operational ve'icles, except the AUGUSTE PICCARD, are air transportable.

Manipulation

There are a wide variety of manipulators (representing some 13 manufacturers) available and in use on present submersibles. They range from very simple 2- and 3-function manipulators to complex, sophisticated arms incorporating seven and more degrees-of-freedom and force-feedback. The ADS's employ the ultimate manipulator (the human hand and arm), but encapsulated in a manner which does not permit full utilization of the hand's tactile and sensory perception. In spite of a few manipulator manufacturer's who refer to their products as being equivalent to the diver's or human's arm and hand, there is no manipulator available or in development which can equal the human counterpart.

The major obstacle mechanical manipulators face in conducting NDE tasks is that the majority of commercial, currently available NDE devices were designed to be used by divers. Nonetheless, a number of offshore service companies have modified such equipment for mechanical manipulation to perform many of the tasks which divers are performing, these include: cleaning, c-p monitoring, photography, TV, current density measurements and ultrasonic thickness measurements. Three areas of NDE: magnetic particle inspection, ultrasonic flaw detection and radiography, have not been conducted successfully underwater by mechanical manipulation and it is highly unlikely, owing to the manipulative dexterity required, that these examinations will be capable of being conducted in the near future. This is particularly true of mpi and ultrasonic flaw detection, however, there are developments underway which are aimed at conducting radiography by means of mechanical manipulation. (See following chapter.)

Surface Support Requirements

The supporting and maintainance of a submersible system can be very little or almost as extensive as a saturation diving system. The more complex the vehicle, the more complex its support. Lockout submersibles, for example, require surface decompression chambers, breathing gas supplies, medical facilities and a range of human talents as wide-ranging as those required for diving systems. In essence, they are no less than self-propelled, untethered diving bells with all the surface support requirements pertaining thereto.

All submersibles require a support platform (mobil or fixed), a launch/retrieval device (for offshore operations), maintenance and repair facilities, navigational and tracking facilities (optional) and crewing accommodations. This latter requirement can be for up to as many as 10 and a ship's complement from 20 to 34. Since some of the larger vehicles have an in-air weight up to 24 tonnes, the launch/retrieval device is substantial. On the low side of surface support requirement are the ADS's which Earls (op. cit.) reported require upwards of 10 tonnes of equipment. Although figures are not available, it is likely that 3 to 4 times this would be required for a medium depth range, 1-atmosphere untethered submersible.

Station-Keeping

Station-keeping capabilities and requirements vary considerably. The tethered Observation/Work Bells and ADS's, because of their cable dependence on surface support, are held to requirements much like the diver. The untethered submersible, however, operates irrespective of the location or station-keeping capability of its support platform, providing that it does not drift off station beyond accoustic communications range.

A major, if not the primary factor in the ability of a submersible to hold station is the pilot's expertise. All vehicles are designed to maneuver in three dimensions and with some capability to hover or maintain station, but their performance varies greatly according to the pilot's experience and innovativeness. Underwater NDE, except for general visual/photo-optical inspection, requires that a vehicle precisely maintain station while the manipulators conduct the examination. To obtain the required stability a number of options are available. Dynamic station-keeping, obtained by the vehicle's thrusters or static station-keeping, obtained by trimming the vehicle to neutral buoyancy, are each a possible, but impractical, solution. In both cases, the moment force is applied to the structure by the manipulator the vehicle will move. Dynamic station-keeping can be and is often obtained, however, by thrusting against the structure or, as described by Sheader (op. cit.), thrusting against the umbilical's catenary to obtain a steadying effect. Another form of dynamic station-keeping can be obtained by using the prevailing current as the force which holds the vehicle against the structure. For long-term station-keeping, however, some form of structure-grasping device is employed. This may be a manipulator, magnetic clamps, suction cups (stickey feet), or metal straps. Given time, there are few circumstances in which some structure-grasping device cannot be conceived and fabricated to obtain the required stability.

Station-keeping or course-keeping while inspecting a pipeline is a different proposition since the majority of the work is done without making physical contact. In this task an automatic pilot can be used to assist, but the main chore is one of balancing off the vehicle's thrusters against the prevailing current. The less the visibility range, the closer the vehicle must stay to the pipe and, consequently, finer control requirements. One might conceive of running on the pipe, but there is always the possibility of cracking or damaging the concrete or protective coating.

Absolute values regarding the upper limits of currents under which a submersible can operate are, therefore, impossible to obtain and, recognizing the differences in pilot experience and vehicle propulsion/power capabilities, difficult to generalize. However, as a general rule of thumb, the practical limits are somewhere between 1.5 to 2.0 knots. This also depends on what type of inspection the vehicle is conducting and the current direction. For example, on a pipeline inspection a 1.5 to 2.0 knot current might be manageable if it is setting into the vehicle's bow, but totally unmanageable if it is on its beam.

Dive Duration/Power

Dive duration is controlled by three factors: life support, power supply and vehicle habitability. The average life support duration for currently operating manned submersibles is 93 hours (3.9 days)/occupant. The minimum is 17 hours/occupant; the maximum is 228 hours (9.5 days)/occupant. These values

include the emergency life support supply.

Electrical power in virtually all untethered commercial submersibles is provided by lead acid batteries. Quite naturally, the total power available on each vehicle depends upon its battery-carrying capability. The following are battery-supplied power ranges for currently operating vehicles.

Submersible Type	Min. (KWH)	Mean (KWH)	Max. (KWH)
1-atm, untethered	4.5	43.5	230
Lockout	36	56.5	164
O/W Bell	25	33.9	65

Not included in the 1-atm, untethered class is the AUGUSTE PICCARD which has a total power supply of 750 KWH, but is some 3 times longer and 3 to 4 times heavier than any other submersible, placing it, literally, in a class by itself.

Also not included are all ADS's (excluding JIM) and several 1-man vehicles and Observation/Work Bells which receive power from the surface via an umbilical. These are generally considered as having an unlimited power supply duration.

Vehicle habitability is difficult to quantify, but easy to recognize. What it refers to is the ability of a human being to remain comfortable and work effectively within the restricted confines of a submersible. There is a limit to what can be done to make a sphere or cylinder without standing headroom comfortable. There is also a limit to the working effectiveness of a human inside a cold (power is too limited to provide heating), damp shell, Consequently, while one can endure such conditions for extremely long periods, his or her work effectiveness expires in a relatively short period. The capability of having unlimited power, although attractive and highly useful, does not mean that the vehicle operates for 12 or 24 hours without surfacing. The pilot of the 1-man WASP is replaced on the average of every six hours, and if the work is under high stress conditions, every four hours is recommended (Sheader, op. cit.) In the much larger 3- and 4-man vehicles, available space for humans is still at a premium, and after 4 to 6 hours enthusiasm begins to wane.

Owing to the constraints outlined above, submersible working dive time of 6 to 8 hours is average. Longer periods have been, and are frequently logged. But, on a regular day-in and day-out routine inspection basis 6 to 8 hours is both the power limitation and the human limitation. For these and other reasons when a round-the-clock operation is required it is normal to engage two vehicles and two crews which alternate between work and rest/battery-changing shifts.

An exception to the above is the submersible AUGUSTE PICCARD. This submersible has a pressure hull of 3.1 m OD and 18.2 m length and has crew bunking and mess facilities. Its crew numbers 6, there is room for 3 observers and life support extends for 90 man days (10 days/occupant). With such commodious accommodations dive durations of days can be carried out in comfort. Obviously, a vehicle of 28.5 m LOA and 168.3 tonnes displacement will not be called on to examine the interior of a structure, but for long duration

pipeline or cable inspections it has significant potential.

Reliability

Manned submersibles have had some 20 years to develop, test and improve their various components. Some vehicles, the research vehicle ALVIN and the DIVING SAUCER, for example, have been diving for over 18 years and, in some instances, support crew members who began working when the vehicle was launched are still with the vehicle. In such circumstances the vehicle's reliability is virtually 100 percent. The reliability figures given the submersible used in Freeman's (op. cit.) investigation are somewhere near the other end of the spectrum. However, he does relate that the submersible's performance was dramatically improved during the contract period. Like virtually any other piece of machinery, the more experience one has with it the better it will perform, providing its design, fabrication and materials are fundamentally sound. Submersibles are a combination of mechanical and electrical components, the greater the reliance on electronics, the longer is the road to obtaining a reliable vehicle. There are no figures available concerning vehicle-by-vehicle reliability, but as a general rule of thumb: reliability is inversely proportional to dependence upon electronics and directly proportional to accumulated dive time. The major problem areas almost always reside in thrusters and electrical connectors and penetrators. One can expect that a manned vehicle which has been operating for two or three consecutive diving seasons should be capable of providing reliability figures equal to those of diving systems. The distinction is noted, however, that newly developed NDE instruments or tools which debut on a submersible are subject to growing pains of their own, which are sometimes incorrectly related to the vehicle's reliability.

6.3.3 Remotely Operated Vehicles

The first known record of ROV operations began in 1952. For the next 22 years their numbers and employment increased modestly, mostly as developmental/experimental projects pursued by various governments. By 1974 some 20 tethered, free-swimming vehicles had been produced, 15 of these were government (primarily military) vehicles. Today over 300 vehicles have been produced and well over 90 percent of these are commercial developments. Earlier in this report it was noted that there are 53 different types of ROVs and 35 different manufacturers (this includes commercial, academic, government and non-profit institutions), some of these vehicles have been operating for upwards of 10 years, others for less than a year. Some are not much larger than a basketball, others are as large as a small car. In view of this wide range of operating experiences, designs and capabilities, the following discussion represents a very broad generalization.

Personnel Safety

ROVs do not jeopardize human life since the vehicles are all unmanned. The only exception may be in the event that a diver or swimmer is employed during launch or retrieval.

Depth

Present commercial ROVs are designed to work in depths in excess of 2,000 m, although none has been called upon to do so. Military ROVs have

worked in 6000 m depth. Depth, therefore, is no limiting factor in ROV application.

Personal Judgment

Since the operator is not exposed to any potential dangers, there are no stress factors involved in his judgment other than those of not entangling or damaging the vehicle. Consequently, the vehicle might venture into areas where the diver or a manned submersible may find too hazardous. The engineer or surveyor who can observe the scene on his own TV monitor has no such qualms and can conduct his observations completely relaxed and in comfort and safety.

Engineering Expertise

Since there is virtually no limit to the number of TV monitors which can be used to monitor the underwater TV camera, there is also no limit to the quantity and type of individuals doing the monitoring. With this advantage, the ROV permits bringing the widest range of engineering expertise to bear on the problem. Their only limitation being the quality of the picture. There is, to some degree, a disadvantage brought about by the necessity to view in only two planes. Although there are devices which provide 3-dimensional TV viewing, they are, like the earlier ROVs and color TV, presently regarded as not much more than a technological curiosity. If a 3-dimensional view is required, stereophotography can be brought to bear which provides quality equal to the human eye and, most significantly, from which dimensions can be obtained.

Payload

Most operating ROVs have a very limited sensor payload, ranging from 5 to 20 kg. Large vehicles (over 1700 kg weight in air) of the TROV, FUGE, SCARAB variety have payload capacities which can accommodate a suite of NDE instruments. TROV, for example, can be fitted with the same instrument suite as shown on the Intersub manned submersible in Fig. 15. Small vehicles (less than 300 kg), however, of the RCV-225, DART, TREC, IZE variety can generally carry no more than their standard equipment, i.e., TV, light, still camera. Under certain conditions small NDE devices such as a c-p probe or ultrasonic thickness meter have been deployed. But in the main these vehicles are restricted to visual/photographic/TV inspection and documentation. Medium size vehicles (300 to 1700 kg) of the RCV-150, SCORPIO, SNURRE-2 variety can be equipped with manipulators which can carry and deploy the majority of NDE c-p and ultrasonic devices (as well as photo/video equipment) described in section 5.1. Consequently, while the majority of operating commercial vehicles are small and have limited payload capacity, there are other varieties which can accommodate virtually any NDE equipment carried by manned vehicles.

Transitting Range

ROVs have demonstrated an excellent capability for conducting long-range pipeline and cable inspections. This has been accomplished by inclusion of a launch cage or clump to the system which, by virtue of its weight, holds the umbilical taut and permits the vehicle to work and maneuver on a short length of cable while the surface ship live-boats above it. Several hundred, perhaps thousands, of kilometers of pipeline has been inspected by ROVs in this fashion

and with variations on this theme. There is some question regarding the depth to which this type of inspection can be effectively pursued by ROVs. The uncertainty resides in the drag imparted on the cable beyond a certain length and the power of the vehicle to overcome this drag. Present live-boating depths by ROVs do not extend much beyond 300 m depth. (This limit should not be confused with the ROVs ability to work greater depths while the supportship station-keeps above it, work tasks have been conducted by ROVs in depths far greater than 300 m.) Recent improvements in ROV propulsive power, such as International Submarine Engineering's HYSUB, may extend this range to much greater depths. But live-boating experiences with ROVs in depths of 600 and 1000 m have been somewhat short of what was anticipated. Regardless, for foreseeable Arctic depths the ROV should be able to operate satisfactorily in a live-boating mode.

Availability

The present and future world-wide inventory of ROVs will adequately supply Arctic needs. All of these systems are transportable by air, ship or land conveyances.

Manipulation

Manipulative constraints on ROVs follow much the same lines as those of manned vehicles. ROVs have been equipped with both rate-type manipulators (where the maneuverability of the arm is stated in degrees-of-freedom or motion of which the arm is capable) and anthropomorphic master/slave system type manipulators (where the master controller actually follows the arm motion of the operator and translates this motion to a slave manipulator remotely mounted, a portion of the force encountered by the slave arm is fed back to the master controller to permit the operator to "feel" the work chore). The ROV ORCA was fitted with two 7 degrees-of-freedom rate-type manipulators, which served to hold the vehicle steady or to hold a work piece, and a force feed-back master/slave manipulator for performing work requiring high dexterity. Manipulation suites, of this complexity, weight and bulk can only be accommodated on large ROVs. The majority of ROVs are not large vehicles and therefore generally only carry one rate-type manipulator, if at all. Stability in the presence of currents and when executing force, and reduced visibility affects the ROV's ability to carry out manipulative tasks the same as with manned vehicles. Additionally, the limited payload of the small and medium size ROVs does not normally permit them to carry facilities for changing tools underwater or to replace broken tool components underwater.

There is an additional manipulative problem which is unique to ROVs and was discussed earlier: the ability of the operator to view only in 2 planes. The diver and manned submersible operator are afforded the use of depth perception, the ROV operator generally does not have this capability. Consequently he must at first literally "feel" his way into the task until some perception of spatial relationship between the manipulator and the object being worked upon is obtained. Once this has been obtained the work proceeds at a pace commensurate with the operator's ability to work under such conditions. According to ROV operators, the lack of 3-dimensional viewing has not been more than an initial minor irritant.

Surface Support Requirements

ROVs have been operated from conventional surface ships, barges, drilling and production platforms, dams, huge submersibles and ice caps. The size of the vehicle, its surface support equipment and the nature of the job dictate the surface support requirements. The ROV system, like its diving and manned vehicle counterparts, requires far more support in terms of hardware and equipment weight than is represented by the vehicle itself. Above water the vehicle is dependent upon a power supply (sometimes provided from the platform) a control/display console, (in an appropriate enclosed space) an umbilical cable and winch, a launch/retrieval device, maintenance/repair facilities and berthing/messing for the operating crew which can range from as 2 to upwards of 10 or 13 for extended 24-hour operations. Relative to its total surface supporting equipment weight, the vehicle itself can constitute as little as 2 percent to as much as 87 percent, 24 percent being average. In terms of mass, this can range from 20 kg to 4,500 kg with the small vehicles to between 7,200 kg and 40,000 kg for the large vehicles. Calculating averages for supporting equipment weight produces 1,200 kg for small vehicles, 6,800 kg for medium vehicles and 17,000 kg for large vehicles. On the whole these are much reduced requirements than saturation diving systems and manned submersibles, but, with the large vehicles, far in excess of what is required for the Atmospheric Diving Suit.

Maneuverability requirements for the support platform depend upon the type of inspection being performed. For inspections conducted at one site, such as a structure or subsea wellhead, the requirements are similar to those of a diving system. For pipeline inspections where live-boating is in progress, the the support platform must stay within a prescribed area or "footprint" above the vehicle in order not to pull it off station. In this procedure a bow thruster is virtually mandatory; a bow thruster and twin screws are ideal.

Station-Keeping

The overall problems of ROV station-keeping parallel those of the tethered submersibles and the diver. Some vehicles have automatic dynamic depth control which greatly simplifies the problem. Others have variable ballast systems which permit the vehicle to obtain negative buoyancy and remain stable on the bottom while performing manipulative work; while others, SOP and SPIDER, obtain stability in the vertical by virtue of their submerged weight, 900 kg and 835 kg, respectively. Also like the diver and submersible, the ROV can grasp a structure by various means to gain stability for working. And, like the submersible, the operator's experience and expertise are critical.

Estimates of ROV station-keeping capabilities in currents when working in an area where grasping or bottoming the vehicle is not possible vary. Some operators claim that they can work effectively and hold station in upwards of 3.5 knot currents. However, the vast majority of ROV operators contacted during this study feel that their vehicles can work in 1.5 knot currents, but that 2 knot currents are the upper limit. Some of the contradictions surrounding these values are brought about by the difference in surface current *vs* bottom current. In the Gulf Stream, for example, where surface currents can be in excess of 3 knots, the bottom current, at 500 m or so below, can be less than 0.5 knot. (Indeed, in some instances it can be setting 180 degrees opposite the surface current.) There is some speculation that such condition, may have been present when claims to working effectively in 3.5 knot currents were made.

Dive Duration/Power

Since there are no life support requirements and all power is supplied to most vehicles from the surface, their dive duration is generally considered unlimited. But, like the ADS and one-man submersible operator, the ROV operator also has factors which limit his endurance, such as the complexity of the vehicle, the work task, the constrictions of the work area and the degree of underwater visibility.

There is no standard watch bill or personnel allocations between operators. Some stand a watch of two hours on and two hours off, others for 3 hours and some for eight hours. The deciding factor is the nature of the task. When the job calls for intense concentration, such as working inside a structure or working with the manipulators, the duration of an individual's watch is short. Where the job calls for "flying and looking" the amount of concentration called for is less and, consequently, the watch duration can be longer. The length of time for which an ROV pilot can operate effectively at a task calling for intense concentration is surprisingly short. The results of interviews with seventeen ROV operating companies reveal that the effective time span is between one to four hours, the average being 1.6 hours. At tasks requiring minimal concentration the duration range is four to eight hours. (Busby, 1979)

In some operations the effectiveness of the ship's Master can limit the dive duration of an operation. When the surface ship is live-boating or continuously maneuvering to stay within one location the strain on the Master can be intense. One operator stated that eight hours was the effective limit on the Master in such circumstances. Relieving the Master with another officer is not necessarily a viable solution since the expertise required in the relief personnel to maneuver the ship may be lacking.

Reliability

Reliability of ROVs is a much discussed topic. When the commercial ROVs initially made their debut in the mid-seventies their reliability was marginal at best and abysmal at worst. With the passage of time and the accumulation of operational experience their reliability improved substantially. Reliability values for the myriad of ROV types are not available. The only reported effort to obtain such values were presented by J. W. Westwood (1980) of Sub Sea Surveys Ltd. who reports as follows:

> "Under contract to the Department of Energy (OSO) Sub Sea Surveys carried out a short study that produced conclusions relating to several problem areas, in particular the basic vehicle design and the vehicle reliability implications of the relationship between oil companies and vehicle operators.
>
> "From the technical point of view the greatest effect upon reliability is basic design. It is obvious from the type of faults found in early vehicles that their designers had little or no underwater engineering knowledge. With correct maintenance and operation some vehicles exhibit high reliability, an example being the RCV 225. One of the vehicles owned by

Sub Sea Surveys has to date completed 228 days on site as follows:

Diving	3,380 hours)	
	)	possible working time
Breakdown	120 hours)	
Standby	1,970 hours	
Total	5,470 hours	

"The above means that the system was available to work for 97% of the possible working time. Similar figures are now being achieved by larger vehicles particularly where certain crucial design specifications are incorporated. In these cases it is reasonable to expect 95% 'reliability'"

It should be noted that the RCV-225 has had some eight years to reach the impressive reliability values observed by Westwood. This contrasts sharply with the 62.9 percent observed by Freeman (1980) from a newly developed ROV.

6.4 PIPELINE PIGS

Companies providing pipeline pigging services are, for the most part, understandably reluctant to discuss at length the pigs' limitations. Likewise are their customers not enthusiastic about divulging such information. Consequently, the information in this section regarding pig performance is limited in comprehensiveness and only to specific pigs. More conventional pigging, such as batching, cleaning, gaging, dewatering, etc., are not discussed herein. Such techniques, although a critical pre-inspection function, have been developed over a long number of years, and seem adequately performed by present technology. The interest herein is directed toward intelligent pigs which provide information regarding a pipeline's integrity.

The following information was obtained from an unpublished manuscript by R.F. Swick, Ashland Pipe Line Company, Lexington, Ohio, regarding the limitations of the Linalog Logging System. It should be noted that in spite of the following limitations, the Linalog System has been in commercial use since 1965 and has inspected some 80,000 km of pipeline for over 100 companies.

- Mandrel marks made inside seamless pipe during manufacturing can cause false readings, sometimes magnifying corrosion and sometimes masking it completely.

- The wall thickness of each section of pipe must be known, since the Linalog measures only comparative thickness. Where wall thickness differs from section to section, as in areas where portions have been replaced by newer pipe, similar corrosion pits may show up completely different.

- The pitting depth compared to log indications over 50 percent of the wall thickness is limited. An example is that a pit depth of .250 in .322 wall pipe would look the same on the log

as a .200 pit depth. This limitation should be considered in establishing a grading classification prior to running the Linalog.

-The only means of grading and analyzing the final log is by manual observation. The shortcoming here is that when a person looks at blips of all gradations for many hours his quality of grading changes. Therefore, the log is given joint corrosion classifications that are in error. The solution to this problem would be to use a computer to grade and analyze the logs, however at this time (ca. 1980) it is impossible to program a computer to cover the wide spectrum of indications produced on the log.

-Foreign metallic objects attached to, or in contact with the pipe may be interpreted as pits or corrosion.

Alexander et al (1981) discussed the positive and negative aspects of a specially designed intelligent pig for inspection of Total Oil Marine's 730 km long, 81 cm (32 in.) diameter pipeline from the Frigg Field. Their observations, which follow, have application to the field at large, as well as to the particular pig developed for this task.

-No defects can be detected less than 7.5 cm from either circumferential welds or longitudinal welds.

-The pig indicates some unclassified defects and defects of less than 15 percent wall penetration are not detected.

-Longitudinal defects with a width of less than 2.54 cm (0.5 in.) are not confidently detected.

One of the more obvious problems is the possibility of the pig getting stuck in the pipeline. While this can and has occurred, it is common practice to initially clean and gage (Kaliper) the pipeline and then to send a dummy pig through the line before sending the instrumented pig. No figures could be obtained regarding the frequency of stuck pigs, but the consequences--particularly in a buried underwater pipeline--are significant enough to take every precaution to avoid its happening.

Constant pig travel velocity through the pipeline is required for best measurements and for location of defects subsequent to the run. In liquid-filled pipelines this is not a significant problem. But in gas pipelines where the pipeline gradient can be high (such as river approaches and in undersea troughs) the pig may advance too rapidly downslope and not obtain the quality of measurement desired. Too rapid advancement might also result in damaging the pig's sensitive components when it comes to an abrupt halt at the bottom of the slope.

Navigation or re-establishing the pig's position during the run can and cannot be a problem. The Linalog System, by recording girth welds, valves, flanges or other full-encirclement objects and by recording linear progress with steel wheels, maintains a very close check on its position. Pigs which do not have this wide array of tools for marking its progress can find trouble

in determining their precise location during the run. Tracking of pigs equipped with acoustic pingers is a practice in oil-or liquid-filled pipelines where the sound can be transmitted through the liquid and then through the pipe to the water/sediment. Gas-filled pipes do not provide an acoustic transmitting medium and therefore other techniques might be employed. One such technique is an eccentric cam on the pig which regularly makes contact with the pipe to produce a sonic pulse. In some instances, where acoustic techniques are used to examine the pipe, the sound produced for tracking may interfere with the measurement technique.

6.5 ARCTIC OCEAN NDE IMPLICATIONS

In certain respects the Arctic Ocean, in spite of its hostile nature, might present less problems for underwater NDE than do other, non-polar ocean areas. On the other hand, its sub-zero water and air temperatures, the tremendously destructive ice forces and the problems of logistics will always make it a force to be reckoned with, even in the mildest of times. The following discussion relates environmental and working conditions to the various NDE techniques described earlier.

One salient observation resulting from this study should be emphasized: there are no indications that conventional NDE devices as now used cannot be used in the Arctic. Hostile as the Arctic can be, there is no evidence to show that the current inventory of NDE devices will not work to their full effectiveness under polar conditions. There are major potential problems, however, but they reside in the methods of employing the devices, not the devices themselves.

6.5.1 Operational Logistics

In section 1.2.1.a the current Beaufort Sea operating window was given at between 110 to 130 days between July and October. Section 6.1 quoted Smeadly of Lloyds Register of Shipping as reporting that the short North Sea weather window and the high degree of platform production activities necessitated downtime of about 150 percent in excess of that employed for useful underwater work. In view of these considerations, the effective working window for Arctic NDE will probably be shorter than that of the North Sea. Even the North Sea winters, as harsh as they are, do permit occasional periods which can be used to refurbish, maintain or conduct minor platform repairs. During Arctic winters all drilling from floating structures stops, as does non-air transportable provisioning. The time which can be devoted to inspection, therefore, will compete heavily with time for reprovision and potential maintenance/repair tasks. The present Arctic inspection requirements do not call for inspecting a certain percentage of structural welds, this practice would appear advisable until some appreciation of the actual time which can be devoted to inspection is gained.

6.5.2 Ice

Ice can be both a hindrance and a help to underwater NDE. On the positive side, the offshore Arctic is the only present location where a diving operation can drive offshore to work and the support platform is, in the winter, virtually of unlimited magnitude. Also, the presence of an ice covering negates confronting sea states which curtail operations elsewhere. On the negative

side is its mere physical presence which must be penetrated, removed or pushed aside and contended with for all but a few months of the year.

The major foreseeable effects of ice on underwater NDE relate to its gouging and to its migration. Regarding ice gouging, its major effect is to require depths of burial and backfill heretofore never confronted. Present pipeline offshore burial depths are in the neighborhood of 2 to 3m to prevent or reduce damage from trawls and ships' anchors. Backfilling is generally accomplished by natural sedimentation processes, but from time to time is done by the contractor to afford pipeline stability. Backfilling cover thickness varies from between 1m to 3m and the material may be sand or gravel or combinations thereof. In order to avoid pipeline damage by ice gouging Arctic pipelines must be buried and backfilled, probably from water depths of 50m or so into the shoreline. The depth of burial has not yet been determined since present knowledge of the characteristics and frequency of gouging is incomplete. In section 1.2.1.d undocumented gouges to depths of 10m into the bottom have been reported, 6.5m gouge depths have been documented in the Candian Beaufort and 5.5m in the Alaskan Beaufort. If an average gouge depth of 6m is assumed, then, at a minimum, 6m of backfill will be required. (These figures are totally unsubstantiated and only used to gain an appreciation for the scope of the problem.) Obviously, visual inspection of the pipeline exterior is impossible, likewise are the present c-p monitoring techniques for buried and partially buried pipelines described in section 5.1.6 which can only detect an anode through backfill thicknesses of 2 to 3m at best. Under these constraints, "conventional" external pipeline inspection techniques will not be effective in Arctic areas where ice gouging is a possibility and the examination task is, therefore, solely in the domain of the intelligent pipeline pig.

The second ice-related constraint has to do with its migration; once again the impact is primarily on pipeline inspections but, in this instance, it is seasonal and dependent upon the type of ice. All NDE equipment deployment techniques now in use depend upon an umbilical cable to the surface for power, life support, command/control, heating, data telemetry, etc. (The only exception is the 1-atm manned submersible which operates independently of an umbilical.) To deploy these platforms (i.e., the diving bell, ROV, ADS, Observation/Work Bell) on a year-round basis in the Arctic facilities must be available to cut a hole in the 4 to 5m thick ice and to maintain the opening. Such facilities are available and have been used. The major problem now becomes one of the ice cap migration. In the landfast or bottomfast ice zone the migration or movement is reportedly minimal and only a problem during storms and in early winter/late spring when the ice is forming or deteriorating, respectively. Pack ice, on the other hand, can present severe problems. The average drift rate of pack ice is 2.5 km/day, and it has been reported at up to 25 km/day in the spring. The problem becomes manifest when a tethered system is deployed through a drifting hole. In the space of several hours the system simply comes to the end of its tether and must be recovered. One alternative is to continuously maintain an opening in the ice above the work-site. Although this may be feasible, it would be a logistic and economic nightmare. Another alternative, in areas where ice-free conditions do prevail, would be to wait until summer. This is probably the course which will be taken, but the repercussions are: 1) only a small fraction of the year is available for pipeline inspection, and 2) the weather/operational window for NDE is extremely short. A third factor, albeit one for the more distant future, is that none of the tethered techniques can be employed in a conventional manner in the permanent pack ice zone.

The untethered vehicle was mentioned as the only capability not effected by ice migration. While this statement is true, the practicality of conducting safe operations is speculative. Several factors enter into the submersible's effectiveness. First are life support and habitability considerations. Inspections of unburied pipelines by manned vehicles do not generally exceed six to eight hours. It would appear that from a cost effectiveness viewpoint six to eight hours would not be economical. From a safety point of view underice submersible operations would be chancy at best. The problems are those of reliability and power. In the open ocean the loss of one critical thruster does not constitute an emergency since the vehicle can surface almost anywhere. Underice the loss of a critical thruster could be disastrous for it could result in the ability to do nothing more than run in circles. At worst, a complete loss of power could halt the vehicle and permit it to surface only directly up under the ice. Although submersible operations have been conducted under ice, they were performed with a safety line attached to the vehicle which could pull it back to safety in the event of power or propulsion failure. This procedure does not provide the economical, wide-ranging capabilities required. One possible alternative is a submersible of the size, duration and power of AUGUSTE PICCARD equipped, as it is, with an ROV which can be deployed to perform the delicate maneuvering required around the pipeline. The problem of reliability, however, still remains.

In essence, the presence of ice and its gouging capabilities result in four conclusions: 1) intelligent pigs will probably be the only feasible method for inspecting buried pipelines; 2) "conventional" tether-reliant vehicles and systems cannot be used for pipeline inspection in the winter months or at any time in the permanent polar ice cap; 3) unburied pipeline inspection must be conducted in the ice-free summer months, if conventional techniques are used, or by improved, long-duration, reliable manned submersibles; and 4) the most potentially attractive technique for inspection of both buried and unburied pipelines is the intelligent pipeline pig which can be deployed regardless of ice cover extent and at any time of the year.

The foregoing discussion purposefully did not discuss production platform inspection. This is a special case which is treated separately in section, 6.5.8.

6.5.3 Currents

Although long-term, measured current data are not available from the Arctic area, the data which are available indicate maximum speeds from 60 cm/sec (1.2 knots) in the Beaufort Sea to 75 cm/sec (1.6 knots) in the Dolphin and Union Strait. The discussion on current speed limitations in section 6.3 regarding the diver, manned submersibles and ROVs states that currents of 70 cm/sec (1.5 knots) can be accommodated and speeds up to 102 cm/sec (2.0 knots) are manageable. Until other current data from the Arctic are forthcoming which show speeds in excess of 102 cm/sec, prevailing measured currents are not restrictive to conducting underwater NDE.

6.5.4 Water Temperature

None of the NDE techniques and none of the systems used to deploy them would be precluded from Arctic application on the basis of water temperature. A few individual devices within the ultrasonic thickness and flaw detection categories are nominally limited to $0^{\circ}C$, but other devices within these categories

can sustain much lower temperatures. The major temperature limitations are in air temperatures which exceed the minimal water temperatures. The potential problem here is the possibility of umbilicals becoming brittle or that some of the devices, such as mpi devices, which contain fluid reservoirs might freeze. However, it is anticipated that virtually all operations will be carried out from within closed, heated shelters. The most typical problem caused by the differing air/water temperatures is that caused by immersing the instrument in the water, retrieving it to the surface and then reimmersing it. In such instances the sea water inside the instrument freezes in the colder atmosphere and does not thaw out when reimmersed.

6.5.5 Sea State

Owing to the relatively short fetch provided by ice free Arctic waters sea states are normally not more than 2, except during storms. All of the NDE deployment techniques can be launched/retrieved in at least state 4 and much higher. Consequently, sea state does not present the magnitude of problems in the Arctic as it does in the lower latitudes. When it does reach the observed states 6 and 7 during storms, underwater operations are curtailed until the weather abates.

6.5.6 Underwater Visibility

Except in some localized areas, such as off the mouths of rivers, underwater visibility in the Arctic is adequate to perform any of the present NDE techniques.

6.5.7 Permafrost

Permafrost itself does not present a problem to underwater NDE. However, the material which may be used to insulate the permafrost from the pipeline may present problems. At present there is some uncertainty as to the precise nature of the type of insulation which might be used underwater; it is possible that it will differ in certain aspects from that which is used on dry land. Certain problems can be speculated, one such being the sound conducting properties of the insulation in the event that an acoustic pinger is used for pig tracking through the permafrost.

Another possible problem may lie in monitoring the insulation's condition. At this time, since the materials and properties of the insulation are uncertain, there is no means of determining what monitoring scheme, if any, can be used. It may be that the only means of monitoring its conditions is to detect temperature changes at the overburden/water interface or by a pig instrumented to detect heat loss internally. The problem is not likely to be technologically difficult in unburied pipeline, but it could be quite difficult in buried lines.

6.5.8 Structure Inspection

Structure (production platforms, rivers, loading terminals) inspection in Arctic waters could, in certain aspects, be a simpler task than it is in more temperate zones. Reviewing the structures described in section 3.0, one can envision an inspection scenario that looks at the structure primarily from inside out, rather than from outside in as is performed on conventional offshore structures.

Production facilities on gravel islands, caisson-retained, ice islands and inside a tunnel are, from an inspection viewpoint, essentially no different from those on land. Consequently, whatever NDE is necessary can be performed as it is on land or underland. Inspection of the seaward portion of the caissons, ice and gravel retainers could likely be performed by gross acoustic techniques such as high resolution side scan or scanning sonar. Essentially, such inspections would entail ascertaining that the configuration or pattern of the seaward abutments is the same as it was when installed. Since pattern recognition techniques are rapidly evolving into highly useful and practical tools, application of such techniques to this type of acoustic inspection would appear within the state-of-the-art and remove the laborious burden of human interpretation/comparison of subsequent inspection records.

Fixed steel structures, such as barges, cones, and monocones and floating caissons offer unique opportunities for NDE. In these structures all supporting members, rivers, sacrificial anodes and other components are contained within a water-filled protective shell or shells. Consequently the interior should provide calm, currentless, ice-free water year-round, ideal conditions for performing NDE on the components within. The absence of ambient sunlight should not be prohibitive since artificial light can be used. The most likely critical inspection area would be the protective shell itself. This can be examined from within using the same techniques as are used to examine fixed structures with no protective shell. External examination of the shell can be conducted during the ice-free season from the structure or a barge. In the monocone concept, where the conical collar is moveable up or down, it may be possible to move it upward and out of the water to inspect the splash zone in-air, rather than underwater. It is likely that these structures will have a double hull, in this instance the separation of hulls is critical concerning what type of deployment technique is applicable (i.e., diver or ROV). One aspect of this type inspection worth noting is the possible difficulties which may evolve through positioning around the structure. The massiveness and essentially featureless nature of the protective shell requires some form of marking to which the inspector can reference his measurements.

Subsea production facilities, wet or dry, can be inspected similarly to present techniques used in ice-free areas. The only difficulty foreseen is that if the inspection is to take place in areas where the ice cover migrates, then it would probably be restricted to the summer months.

6.5.9 Meeting Inspection Requirements

The preceeding topics in this section (6.5) discussed the ways and means by which NDE of Arctic pipelines and structures could be conducted. In the main, virtually every underwater inspection requirement which is being met elsewhere in the world oceans can seemingly be met in the Arctic by appropriate scheduling and utilization of an appropriate sensor deployment vehicle or system. This does not mean there are no uncertainties. Chapter 8 identifies certain areas where these uncertainties reside and suggests possible routes to their ultimate solution. However, when comparing existing and proposed U.S. and Canadian inspection requirements against the means of carrying them out, certain NDE requirements seem to offer a greater degree of difficulty than others. Two areas within this category are pipeline corrosion protection system monitoring and leak monitoring.

The U.S. Office of Pipeline Safety and the Canadian Department of Energy, Mines and Resources require an annual monitoring of the pipeline's cathodic protection system. As discussed earlier, this requirement can adequately be met on unburied and buried pipeline to burial depths of not more than 3 m on c-p systems using sacrificial anodes. Pipelines buried deeper in zones where ice gouging is a potential may be beyond the capabilities of present or future c-p monitoring techniques; these include pipeline pigs and divers or vehicles.

The Office of Pipeline Safety also requires that surface conditions be inspected on or adjacent to each pipeline right-of-way if evidence exists to show that inspection is required. Normally, for offshore pipelines, the type of inspection which is conducted is carried out by aircraft overflights of the pipeline route during which the crew visually scans the sea surface for surface indication of leakage such as bubbles or slicks. Except for ice-free periods in the Arctic, a visual inspection of the sea surface from aircraft does not appear feasible since the ice cap will mask surface indications of leakage. There may be techniques which can be used from aircraft to identify surface or sub-surface manifestations of oil or gas leakage under an ice cover, but none of the individuals contacted or technical publications reviewed during this study revealed what they might be or even alluded to the problem. Assuming there are no such techniques available, the pipeline operator is left with no other alternative but to employ a subsurface vehicle to comply with this requirement. The vehicle might be an intelligent pig instrumented for leak detection, an untethered ROV capable of pipe tracking and leak detection or a conventional manned submersible capable of long duration operations and precise navigational capabilities which will permit it to return to the hole through which it was launched. Whatever the alternative selected, there is no present research being pursued to address this problem in the Arctic.

7.0 CURRENT NDE RESEARCH AND DEVELOPMENT

There is a wide variety of current research and development with direct and indirect application to underice NDE. The majority of this work is not directly aimed at Arctic application, although much of it could, if successful, find employment therein. In earlier sections it was noted that all of the Arctic offshore operators contracted in this study acknowledged the eventual need for and desirability of reliable Arctic NDE equipment and comprehensive inspection programs. Concurrently, all operators were of the opinion that at this point in time (Winter/Spring 1982) it was somewhat premature to invest a great deal of time and funds in developing underice NDE capabilities since there were many preliminary questions to be answered which would bear directly upon the nature and scope of Arctic offshore inspection programs. Not the least of which is the extent of the role pipelines will play as opposed to the use of offshore loading and storage terminals in carrying hydrocarbons to southern markets.

Some of the required technical information concerning pipelines in the Arctic were identified by W.J. Timmermans (1980), and the answers to several have a direct bearing on the type of NDE which can effectively be employed; these are:

-Detailed information on the extent of ice cover to provide a data base for determining the probability of completing a project in a given time period.

-Knowledge concerning the average ice thickness in various areas for estimates of permissible construction loads and development of methods to assess possible damages.

-Information on the interaction between the bottom soil and a grounding ice mass to determine stresses and deformations.

-Determine the frequency of ice intrusions and bottom scour to establish a required depth of burial.

-Determine the effects of a pipeline carrying a fluid of higher than ambient temperatures on surrounding permafrost.

Timmermans further suggests that pipelines will probably need to be buried a conservative depth of about 7.5m in water depths of 45m, or by tunneling or by backfilling the pipe by a gravel berm and/or artificially creating a permafrost mass around the pipe. Of particular interest to underwater NDE was his estimates of open or ice free water in the Alaskan and Canadian Beaufort which he stated as eight weeks inside the Barrier Island, and merely six weeks outside. In view of these and other technical considerations, it does not seem unwarranted to take a cautious and deliberate approach to outlining inspection procedures and techniques until an environmental and engineering data base has been established.

Nonetheless, a limited number of activities have and are conducting R and D which they believe are required for Arctic maintenance and repair and will have application to inspection as well. More numerous are the activities

which are developing NDE techniques for application elsewhere, in particular the North Sea, but their results will also have application to the Arctic. The following describe these activities and their objectives.

7.1 DIRECT ARCTIC RESEARCH AND DEVELOPMENT

7.1.1 Diving Habitat

In a joint venture Kockums Shipyard, Melmo, Sweden and the Norwegian Underwater Institute is developing a deep diving habitat capable of operating on the sea floor for 14 day periods at depths to 350m. The habitat is scheduled for testing in Bergen in 1983 and it is being developed for Arctic conditions and north of 62 degrees latitude. Called DIVING MOSQUITO, the habitat will accommodate 16 divers and an 8 to 12 man crew. The 900 tonne displacement system will have a propulsion system which will permit it to maneuver within a limited area at speeds up to 2 knots. The habitat is designed to support most types of general underwater oilfield work (excluding very heavy lifting) and can be tailored to perform more specific tasks, such as pipeline repair, riser tie-in, inspection and maintenance of subsea completions and blowout prevention. Supplies and fuel would be from an existing supply vessel. Crew change would take place every ten days by either bringing the habitat up to the surface or by using a bell. Advantages claimed by the use of a supply vessel would be in the transportation of heavy components and assistance work needing large spaces. The supply vessel can also be used for other purposes when not directly engaged with the habitat.

The development was instigated because of the high cost of installing and maintaining underwater structures. Currently divers can only work year round in severe sea and wind conditions from a large ship or a semi-submersible. This involves expensive machinery and dynamic positioning systems. There is the added risk of damage to diving bells or underwater vehicles when launching in bad weather. The DIVING MOSQUITO concept seeks to remedy these deficiencies. (Ocean Industry, March, 1982)

7.1.2 Polar Gas Project

The Project involves Polar Gas, Monenco Pipeline Consultants, R.J. Brown and Associates and Can-Dive Services. The goal of the project is to demonstrate the technical feasibility of connecting sections of 91cm (36 in.) diameter pipeline in 503m of water. Initial tests consist of mating two sections of pipe on the sea floor using mating sleds and procedures developed by Brown Associates. The sections will be welded using a 1-atmosphere welding habitat and support devices designed by Can-Dive Services. The point of this demonstration is to show that similar tie-ins can be accomplished in the McClure Strait and Byam Martin North Channel in the Arctic Islands.

Of particular interest to NDE is the welding complex which consists of a 1-atmosphere welding habitat, life support/equipment module, tethered manipulator bell (Observation/Work Bell), a JIM ADS, surface support complex and a bell launch/recovery frame. All components are tailored for Arctic operations and transportable by Hercules aircraft. The bell will be used to transfer personnel to the life support/equipment module to conduct the welding and, among other tasks, perform NDE of the welded joint consisting of ultrasonic and radiographic inspection. The ice cover in the Straits will serve as the launch/

retrieval platform. While the major function of the welding complex and its support equipment/vehicles is to join the pipe sections, the system does provide a technique for conduction pipeline NDE underice. Significantly, the areas where this system is to be operationally deployed is characterized by a relatively stable, land-fast ice-cover.

7.1.3 Underice Profiling

The Marine Systems Engineering Laboratory, University of New Hampshire has recently begun an Arctic oriented program utilizing techniques and concepts developed in its EAVE EAST (see section 7.2.3.a) project. The program addresses the generic problems involved in performing a long range (possibly 1800km) underice inspection mission. The operating scenario now envisioned is to conduct a 10 km mission which takes acoustic profiles of the ice keel and the bottom. At this point six echo sounders (five upward looking and one downward locking) are envisioned which operate on the order of 200 kHz at about 200 watts. A large part of the program will entail investigating vehicle control to assure a high degree of reliability. With respect to the latter, it is hoped to make the vehicle "fall gracefully," if at all, rather than catastrophically, and to be friendly to the user. The program will attempt to implement high level languages into the system--definitely PASCAL, C, if possible. It is also hoped to develop a recording device for the vehicle that will store engineering data and operating parameters during testing, as well as very large quantities of data during the mission. The application of bandwidth compression to the profiling data will also be investigated. A magnetic bubble memory recorder (4 Megabit capacity) is planned for use in the vehicle.

The Bedford Institute of Oceanography at Dartmouth, Nova Scotia has recently contracted with International Submarine Engineering Ltd., Port Moody, B.C. to commence a concept design of ARCS (Autonomous Remotely Controlled Submersible). The driving force behind the ARCS program is an urgent need for bathymetric surveys in the high Arctic where the area, in many instances, is ice-free for only a matter of weeks. The Institute, after investigating new techniques for surveying the Arctic, concluded that one of the more promising techniques is an autonomous under-ice vehicle. The performance goals of this vehicle are: an endurance of 180km, a speed of five knots maximum and a maximum distance from the control station of about 18km. While the vehicle will be truly autonomous, one feature of the system will include the capability of periodically checking its location and performance. At a later date it is hoped to broaden the instrumentation suite to include seismic and side-scanning sonar. The program is currently funded for about three years.

7.1.4 Conventional NDE

Dome Petroleum is utilizing divers and mpi to examine the submerged hulls of four drillships, the first of which has been drilling since 1976. The plan is to begin drydocking the ships in the near future at the rate of 1/year. The hulls will be re-examined by mpi and other techniques in drydock and the results will be compared against those obtained through underwater techniques. The point of the comparisons will be to gain some confidence level in underwater NDE such that the ship can remain in the water for long periods (while being monitored by underwater techniques) without the fear of deterioration or failure going undetected.

The foregoing are the only directly applicable Arctic projects now being conducted that have a bearing on underice NDE. It should be noted that all of the problems identified by Timmermans (ibid.) and Dome are being addressed by Canadian and U.S. government and academic institutions and the offshore operators themselves. Virtually all of these are long-term projects, the results of which will be forthcoming in the mid-eighties and subsequent years thereafter.

7.2 NDE Research and Development with Arctic Application

Research and development in this section is categorized as: 1) Instruments/ Tools; 2) Techniques and 3) Vehicles. This categorization is arbitrary and for convenience only.

7.2.1 Instruments/Tools

7.2.1.a Television Camera

Recognizing that standard TV systems suffer from errors in perspective, restricted field of view and inadequate or marginal picture quality. The UK Department of Energy has contracted with the Sira Institute Ltd., Chisehurst,Kent to develop an improved form of wide-angle full color display covering a field of view of 180 degrees horizontal by 60 degrees vertical coupled with a high resolution center-of-interest presentation of about 8 degrees. The effectiveness of this new form of composite TV display will be assessed by skilled operators on a simulator employing a remote controlled land operated vehicle which will be driven around obstacles on a test course.

If this form of visual display meets with approval, the next stage of the project will be to build the TV camera array on to an underwater test vehicle able to perform typical tasks under the control of a remotely positioned operator viewing the new wide angle high resolution display.

The application of electro-optical techniques to the development of underwater visual systems reflects the DOE's interest in this technology for remote sensing, positioning and inspection tasks.

7.2.1.b Underwater Acoustic Television System

In section 5.1.1 Thorne EMI Electronics Ltd's underwater acoustic television system was described. As of November 1981 the system had yet to be employed operationally by the offshore industry. The technique would appear to have application off the mouths of Arctic rivers during major discharge periods and low visibility.

7.2.1.c Ultrasonic Torch

The ultrasonic torch was described in section 5.1.7.b More recently Ferranti Computer Systems has joined the U.K. Atomic Energy Authority in advancing further development of this device. Design goals include the following (Daiqliesh, et al, 1982):

-Operate satisfactorily in salt water in pressures up to 281 kg/cm^2 (400 psi), at temperatures down to 4^{o}C.

-Be physically rugged, but easy to handle in heavy gloves.

-Require no critical adjustments or positioning underwater by the diver.

-Be neutrally buoyant, including any umbilical cable.

-Require minimum cleaning of the node.

-Be capable of detecting all surface opening cracks above a predetermined size (2 cms long by 3mm deep) and be capable of identifying their position.

-Be capable of rapid inspection.

-Allow the inspection data to be interpreted at the surface.

-Provide a record of the data.

Since the ultrasonic torch is, by design, to be deployed by a diver wearing gloves, it is tailor-made for Arctic diving. However, the 4°C temperature limit is somewhat short for Arctic application.

7.2.1.d Holography

A prototype acoustic holographic device for underwater NDE was developed by the French firm Intersub in 1978. The firm, however, went out of business in 1980 and subsequent development or utilization of this device has not been reported. More recently Watson (1981) discussed the limitations, advantages and applications of underwater holography using lasers. Watson concludes that high resolution, three dimensional images of underwater structures and components could be recorded for non-destructive inspection by holography which could possibly supplant other methods of underwater inspection. The potential problems and limitations imposed by the rigorous environment should, however, not be underestimated, and may be too severe to overcome at moderate cost. The scattering of laser light underwater may seriously degrade the image quality and limit the depth of scene which can be recorded. This in turn may impose too heavy a demand on the amount of laser light (and ultimately the size of laser) required to produce useable holograms. Temperature gradients may give rise to frozen interference patterns on the hologram which may seriously restrict the application of holographic interferometry. The main deterrent to success is likely to be the mammoth task and cost of engineering a system which can be successfully maneuvered and operated underwater.

7.2.1.e Flaw Detection

The Ultrascan III flaw detection device was described in section 5.1.7.b. A recent merger between S & H Diving Corporation, Morgan City, LA and Sylvester Undersea Inspection has resulted in a research and development program aimed at utilizing the device from an ROV as well as by a diver for which it is now designed. The ROV to which it will be tailored is a Perry RECON IIIB.

Also in conjunction with Sylvester, S & H Diving has recently developed a radiography system designed specifically for underwater operations. The system (TH-I) holds 100 curries of IR-92 which will, according to the manufacturer, penetrate 7.6cm of steel. The system can operate in a dry habitat as well as in the wet.

7.2.2 Techniques

7.2.2.a Flooded Member Detection

The British Gas Corporation's Engineering Research Station, New Castle, has developed prototype equipment for the detection of flowed platform members Since jacket structures invariably consist of separate sealed compartments containing air at atmospheric pressure, the detection of internal flooding indicates the existence of a through-wall defect somewhere on the member. For a through-wall fatigue crack this procedure is a preliminary inspection stage as long as sufficient residual fatigue endurance remains once a fatigue crack has penetrated the wall. If a flooded member is found conventional NDE methods would be employed to locate and identify the defect.

A prototype flooded member sensor has been constructed and trials were carried out in the spring of 1981. At its present state of development, the equipment is capable of detecting flooded members at an average inspection rate of about one member per minute, using divers who do not require any NDE expertise. The presence or absence of water is detected by transmitting an ultrasonic pulse towards the center of the tubular member and interpreting all echoes. The ultrasonic probe is used in 'stand-off' mode--it is held some distance from the surface --and is connected by means of an umbilical to an electronics package in the diver control room. In the case of a flooded member, a reflected signal with a favorable signal/noise ratio is available provided that the probe axis is accurately aligned. In order that a negative indication can be interpreted correctly, it is essential to monitor the probe alignment. In the prototype the probe is mounted on a jig held in position by magnetic clamps. Alignment of the probe is monitored by interpreting the pulse form of the first echo from the outside surface of the member. The diver, in telephone contact with the NDE operator, can make any necessary adjustments to the probe alignment though normally his task is simply to place the jig on each member in turn.

Tests on attenuation caused by marine growth showed that soft marine organisms and thin, hard layers of calciferous deposits on the member surface meant very little loss of resolution and need not be removed. It was found to be necessary, however, at this stage of development, to remove thick mussel growth. It is believed that improvements in the probe characteristics and associated electronics can be made which will permit readings without necessitating structure cleaning. Future developments also include modifying the probe such that it is compatible to an ROV. (Offshore Engineer, May 1981)

7.2.2.b Pipeline Leak Detection

In 1977 Sonarmarine Ltd. developed a pipeline leak detection system incorporating a towed vehicle or fish and acoustics. Although the system is not a current development it is a unique approach to NDE which could have Arctic potential. The technique employs a hydrophone to detect the sound of a liquid-to-liquid leak, homing in to the maximum noise. For a gas leak a narrow beam transducer scans the pipeline until the pulses reflected from escaping bubbles are detected.

For oil lines a large sonar fish is equipped with two acoustic detection devices--a wide band and a narrow band hydrophone. The fish is towed parallel to the line at 2-7 knots, preferably keeping within 30 to 120m of it on either side if the line is unburied but closer if it is buried, varying with depth of bury and size of the leak. By this method, a leak so small has re-

portedly been detected that divers were unable to see it at close range and leak rates as low as 7.5l/hr. at test pressure may be found. Signals are amplified and presented in visual and audible form as well as recorded on charts for permanent records.

The system has also been operated from a manned submersible and hand-held by divers. A processor has been developed which filters out interference noise, such as, ships' propellers, porpoises, etc., and incorporates a threshold device which makes the true noise signal more pronounced than surrounding background peaks. (Offshore Services, September, 1977)

More recently, Hydro Products of Dyce has provided a variety of their underwater gas discharge and incandescent lights for use in a research project carried out by Shell UK Exploration and Production.

The project was aimed at improving the detection of leaks in underwater pipelines by direct visual means. The technique is applicable to leak detection during hydrotesting on both gas and oil pipelines, particularly in close proximity to platforms. Essentially the technique uses a fluorescent dye in the hydrotest water which, if leaking from the pipeline, is excited by a light source and viewed by an observer in a submersible using filtered spectacles.

The test program involved comparing selected dyes, filters and light sources. These comparisons were made under simulated conditions in a sea water tank within the Physics Department at Robert Gordon's Institute of Technology, Aberdeen.

Initially, mercury vapor lights were used but later in the program the expected improvement using a thallium iodide light source was examined. As predicted the fluorescence could be observed with a monochrome TV camera. (Sea Horse, Spring, 1982)

7.2.2.c Maintenance Activities Sub Sea Surface (Project MASS)

Project MASS began in 1976 at the University of Strathclyde, Scotland and has lead to development of a system to correlate and identify videotape records for cross-referencing with navigation and survey data. It is essentially designed to provide a precise orientation of the diver or submersible in relation to underwater inspection records. Two individual systems, to be linked together in the final package, have been developed. They are called SARAH (Strathclyde Acoustic Range and Height) and SIMON (Strathclyde Inspection, Maintenance or Navigation).

SARAH will accept signals from any existing underwater acoustic navigation system for subsequent evaluation and position fixing, while SIMON is basically a closed circuit television unit (CCTV) to provide the visual data required to complete job records. At the outset in 1976, position-fixing accuracy offshore was of the order of $\pm$2-5m which the Strathclyde team felt was too inaccurate for the locating of CCTV cameras and NDE testing equipment. Underwater trials of the SARAH software in 1979 in conjunction with Sonardyne gave position fixes of the order of $\pm$1m over 80 percent of the fixes. Further trials in conjunction with Oceonics Ltd. in 1980 brought this improvement to $\pm$0.5m over 80 percent of the fixes. Final underwater trials with the SARAH system were carried out in June 1981. On this occasion the SARAH system was interfaced to Sonardyne's "PAN" microprocessor

based underwater acoustic processor. This was used in conjunction with three Sonardyne Compatt transponders and one DMT (Dual-Mode Transponder) which operates conventionally. The selection of a minimum of three Compatt intelligent transponders allows a complete check on all baseline measurements.

In the June 1981 underwater trials, the measurements were obtained with the transponders distributed around 0.6m diameter piles to simulate an offshore steel jacket structure. Medium frequency (19-36 kHz) transponders were used. The results of these trials showed a considerable improvement over the previous year's trials with a position fix accuracy of $\pm$0.2m with an 87 percent confidence limit. Some 8 percent lay within $\pm$1m with only 5 percent outside the $\pm$1m band. When the transducer was held stationary underwater, a least squares analysis showed the position fix to be within $\pm$0.1m. (Milne, 1982)

The SIMON system uses Hydro Products Surveyor 1 camera which can be hand-held or helmet-mounted. SIMON was designed specifically to work in conjunction with SARAH so that it is possible to monitor on the surface, the diver's depth, speech and position for correlation with the television inspection program recorded on videotape. The topside operator can thus obtain a complete analysis of the underwater operations, and record results on videotape annotated with date, time, depth, location, and any other inspection information required. There is, consequently, a complete audio-visual link between the diver and the top-side operator.

The link is strengthened by including a mini-television monitor in the diver's helmet together with an optical device to enlarge the picture and make the image appear in front of and slightly above the diver's normal line-of-sight.

The display a diver sees is controlled from the surface allowing him to see a variety of displays including the output of the helmet-mounted camera; the same picture, but including added information superimposed from videotape sources (such as graphic display of the output of an ultrasonic transducer); the picture from a separate surface located camera (to relay drawings or diagrams of the structure being inspected), the output of a video recorder, or a separate signal from an external source. (Offshore Engineer, June 1979)

7.2.2.d Vibration Analysis

There are a variety of techniques available and under development which purport to monitor a fixed structure's integrity by measuring natural or induced vibrations. Development of these techniques began in the early 1970's and has continued to the present. While several corporations offer vibrational analysis services, the acceptance of this technique as a substitute or even to augment conventional underwater NDE has been slow. For this reason they are categorized in this chapter as current research and development, albeit, the providers of these services do not necessarily share this viewpoint.

The Minerals Management Service (MMS) of the Dept. of Interior, has for several years, and continues to support fundamental R & D into a variety of vibration monitoring techniques for application to offshore structures. One such program is conducted by Dr. S. Rubin and his associates of the Aerospace Corp. which has as its objective: to assess and advance the utility of vibration measurements for detection of significant strength degradation in steel template structures. Early work by Rubin was in an area he designates as Global Mode Monitoring, a technique based upon the detection of frequency and shifts of node shape in lower

global nodes of vibration. Experimental and analytical studies were conducted on an eight-legged jacket platform in 100 m water depth in the Gulf of Mexico. (Rubin, 1980; Coppolino and Rubin, 1980). A number of significant results emanated from this research which evolved a technique for making quick measurements, inexpensive manpower and equipment costs, safety, and independence of weather and sea conditions (measurements are made above water on the platform deck).

The major shortcomings with the utility of this technique (according to Rubin) are: 1) the uncertain variation of modal frequencies for repeat measurements stemming from unknown changes other than platform damage (e.g., changes in deck mass, soil stiffness, conductor/guide interaction, and in brace flooding); 2) the difficulty to unambiguously identify higher than fundamental global structural modes; 3) the requirement for substantial frequency change in a fundamental mode for unambiguous detection of damage; and 4) the conflicting desire to detect damage before an unacceptable loss of strength has occurred.

Duggan et al (1980), with support from 13 U.S. oil and gas producing companies, investigated the feasibility of using ambient surface vibrational measurements to evaluate the structural integrity of steel template platforms in the Gulf of Mexico. Specifically, the projects sought to establish whether the vibrational behavior of the platforms remained stable under varying environmental and operating conditions but changed due to structural modification. During a 7-month period, over 4,000 hours of vibrational and wave height data were recorded on three typical Gulf of Mexico platforms with varied structural configurations, operating conditions and environmental loadings. On one platform, Ship Shoal 274A (SS274A), major repairs on two legs and the replacement of three braces took place during the monitoring period. Measurements were obtained before, during and after the construction activity on this platform. To a limited extent, data from the three platforms was then evaluated using autospectral techniques. A second project was an analytical study of the SS274A platform. Selected data were analyzed using both autospectral and cross-spectral analysis methods. A new analysis technique, the response shape vector method, was also utilized. Results of the data analyses were then correlated to the results of a series of structural analyses using a detailed dynamic model of the platform. The projects concluded that state of the art ambient surface vibrational monitoring techniques failed to detect the removal of jacket bracing members on the SS274A platform.

More recently, Rubin (1981), with support from the M.M.S., has investigated a new concept termed flexibility monitoring. The concept takes advantage of the basic shear beam behavior of a fixed offshore structure and that the three fundamental mode shapes closely approximate deflections caused by a static load at the deck. The goal is to a-proximate the shear flexibility across individual bays of the jacket as well as gross flexibilities in respect to the foundation. The term flexibility is used to imply deflection per unit force. The forces applied to the jacket are inferred to be proportional to the measured relative deflections of the above-water structure between the deck and jacket top. An estimate of gross shear flexibility of a bay is proportional to the corresponding relative deflection across the bay, divided by the above-water relative deflection. Similarly, by appropriate relative measurements at the foundation, normalized by the same above-water deflection, various foundation flexibilities are estimated. Rubin acknowledges two complications of this new concept: the need for underwater placement of sensors, and the key measurement issue for flexibility monitoring is the accuracy with which amplitudes can be measured. Rubin is currently determining those values from random data obtained by various techniques used on the Round Robin model (see below). The next step will be an offshore investigation to determine accuracy, repeatability, and sensitivity.

R. Kenley and C. Dodds of Structural Monitoring Ltd. with support from the U.K. Dept. of Energy have investigated a form of vibrational monitoring termed Local Mode Monitoring. This form of monitoring relies upon ambient exitation, as does global monitoring, but it monitors individual members using accelerometers placed on groups of members underwater. This technique was evaluated in 1978 with the removal of platform WE from the West Sole field. The platform was deliberately and progressively damaged prior to removal by cutting members and eight accelerometers were placed underwater to measure the local nodes of the K-frame which included the damaged member. The results, according to the investigators, demonstrated that flooding and half severance of members could be detected by local vibration measurements on groups of members. The response spectra were not as well defined as the overall ones and identification of natural frequencies and mode shapes was consequently more difficult and less accurate. The results were similar to those which the authors have obtained on other deepwater platforms and are probably characteristic of most platforms. The local monitoring method is closer in application to conventional inspection than the overal (global) method in that its objectives are to detect local damage. Its sensitivity lies somewhere between that of general visual inspection and that of close visual and NDT inspection for cracks. It is an indirect method of detecting flooding and cracking, however, and suffers from the disadvantage that the results cannot readily be interpreted on site. (Kenley and Dodds, 1980)

A second local mode of vibration analysis has been developed and is marketed by Symirex of Marseille. The theory behind this technique, termed Vibrodetection, is discussed by Lepert et al (1980). In operation a vibrodetector unit is positioned (by a diver) in sequence on each member to be examined. (It is not necessary to clean the member or nodes before testing.) Low-frequency vibrations are created in the member by a shock and both the excitation signal and the response signal are simultaneously measured by means of sensors in the vibrodetector. These signals are transmitted by an umbilical cable to the surface acquisition equipment. Processing of the data establishes the transfer function of each bracing element and this information is recorded.

Repeated measurements are made at the same points of the structure during its next routine inspection and the readings obtained are compared with the original characteristics established during the first recordings. Differences indicate defects that can be localized. Components of the system include a Data Acquisition Unit and the Vibrodetector.

The Data Acquisition Unit processes the measurement signal and is built around a Fourier analyzer with cassette recorder and display unit. It is installed in a small water proof air conditioned container which can be operated from any position on the platform's decks. The Vibrodetector is successively clamped onto each bracing to be tested. Its core consists of a pneumatic hammer with damper and a load cell, which applies (and measures) a shock to the bracing. An accelerometer attached to the base of the vibrodetector, measures the responses of this member. The vibrodetector unit has zero buoyancy underwater. The unit is connected to the surface equipment by an umbilical cable which transmits the signals and also provides the vibrodetector with compressed air.

A third local mode of vibrational monitoring also incorporates induced vibrations and is provided by Applied Dynamics Ltd. under the name of SHRIMP. It consists of the injection of a low level swept frequency signal into the structure at a chosen point and the monitoring of the response at other poihts, thus establishing a particular signature, or datum mark, to which future signatures can be compared.

By use of specialized equipment, the natural environment responses caused by weather and other responses caused by man and machines can be eliminated. A daily or weekly computerized output indicates whether a failure has occurred, where it is located and, in the case of a crack, whether it is propagating or has been arrested. (Salvage, 1982)

The Italian firm Tecnomare has also developed a forced local vibration analysis technique in conjunction with Det Norske Veritas and with financial support from Norsk AGIP. The system is comprised of: three triaxial accelerometer heads and electronics for data acquisition; an electro-hydraulic exciter and, a surface container equipped with data recording and control electronics.

In practice, an underwater model is lowered to the appropriate depth (the module frame contains accelerometers, exciter, hydraulic power pack, cables and hoses ready for operation); the exciter is released from the frame by a diver and clamped to the structure at the prestated location; the accelerometers are released and connected by magnets to the structure at the prestated locations; the data is then collected and recorded. Upon completion the underwater components are returned to the surface.

Prior to the measurement program Tecnomare performs a computer analysis of the structure using modal analysis techniques to select the optimum excitation measurement points. Subsequent to the field work, an in-house diagnostic computer analysis identifies size and location of possible damage. Six excitation measurements can be performed in two days which, according to the manufacturer, is more than sufficient for a medium sized platform in 100 m of water. (Ocean Industry, April, 1982)

The Memorial University of Newfoundland, St. John's, is also engaged in vibrational analysis R&D. The purpose of the research program is to determine techniques for monitoring vibrations of fixed offshore platforms subjected to ocean waves and to assess the change in the vibration spectrum caused by a secondary structural failure. To date, tests have been conducged in air with a K-frame type tower constructed from PVC tube. The vibration spectrum of the undamaged tower was determined experimentally and the resonant frequencies obtained were compared with analytically determined values. The procedures were repeated with one or more members removed from the structure. The shift in the resonant frequencies of the "damaged" tower was observed. (Memorial University of Newfoundland, 1982)

The University of Maryland, with support from the Minerals Management Service and the Office of Naval Research, is evaluating the applicability of the random decrement method (RANDOMDEC) for determining flaws in offshore structures. RANDOMDEC was initially developed in the late 1960's and received rather widespread use in the aerospace industry for the determination of modal damping ratios and the detection of mechanical failures. It is a general method of analysis which is particularly suited to the class of problems in which characteristics are desired of inservice structures to unknown random excitation. The major advantage of this technique is that it requires only measurements of the dynamic response of the structure and not the input excitation causing the response. On offshore platforms, such random input forces occur from wind, waves, and currents. The method analyzes the measured output of a system subjected to some ambient random input. After analysis, a signal results which is the free vibration response or signature of the structural system. The ability to obtain unique response signatures for different modes (usually accomplished by filtering the output) enables detection of early damage before overall structural integrity is affected. Research into application of the RANDOMDEC to offshore structures continues, and future investigations will be made for soil-structure interaction conditions and a model, constructed for

this project, will be tested in water. (Yang, 1981)

7.2.2.e Acoustic Emission Monitoring

Acoustic emission is defined as a class of phenomena whereby transient elastic waves are generated by rapid release of energy from a localized source or sources within a material. Acoustic emission analysis technology utilizes the minute acoustic emissions produced by discontinuity regions in materials under stress to analyze a structure for physical integrity. The acoustic emissions are given off from discontinuities under stress conditions; to use this technology it is necessary that stress be applied to the structure. In monitoring an offshore platform for structural defects the cyclic stress imposed on the structure by wave motion provides adequate stress for analysis.

Determining a structure's integrity by acoustic emission analysis is, like vibration analysis, an emerging underwater technique, although it has been used successfully in onshore application since 1966. Borst (1977) discussed some of the advantages and disadvantages of acoustic emission monitoring. On the positive side this technique is capable of detecting that a defect exists and whether or not it is growing. On the negative side the technique cannot measure the defect's size; it cannot tell what is occurring or how serious the defect might be and, finally, there is not sufficient experience to demonstrate conclusively that the equipment can be installed and operated for many years. The sensing equipment consists of sensitive piezoelectric transducers attached to the structure underwater. Cables transfer the received signals to the platform deck where they are amplified and conditioned electronically and subsequently processed by special computers to identify the location and significance of the discontinuities.

Two industrial firms in the U.S. produce acoustic emission systems for use on offshore structures: Dunegan/Endevco, San Juan Capistrano, California, and Exxon Nuclear Co., Inc., Richland, Washington. Significantly, at this writing there is no U.S. platform which uses acoustic emission monitoring techniques on a routine basis. All applications to date have been for experimental and demonstration purposes.

A recent entry into this field is Kockums AB who has developed a crack detector system which will be tested on a North Sea structure in October, 1982. Production of the system is scheduled for late 1983. Unlike other acoustic crack detection systems, the Kockums technique does not involve permanently mounting the detecting hydrophones to the structure. Instead, groups of at least four hydrophones (with amplifiers and filters) are immersed in the water from the platform for monitoring. The prototype is arranged so that the hydrophones can be moved and adjusted with wire attached to the platform. One cable leads from the unit up to the control room where the measuring and computer systems are located.

Signals from the hydrophones go to preamplifiers, amplifiers and filters through an A/D converter to the computer where the signals are then analyzed. First, the initial crack emissions are characterized and evaluated. Second, the changes of the emission characteristics over a long period of time are studied to determine when the crack is critical. It is also intended to relate the signals to the combined forces of sea and weather together with the weight of the platform. The location of the crack in the structure as well as changes in signal characteristics will be given in the data report. Based on the data obtained, inspection and maintenance programs can be directed toward the most critical areas of the structure.

The Norwegian Institute of Technology (NTH), Trøndheim is also developing an acoustic crack detection technique. Instead of suspending the hydrophones by cable, the NTH approach envisions attaching them to exposed areas of the structure with magnets. From these locations acoustic signals will be transmitted to a computer on the platform and the data can also be sent via satellite to a larger facility on the Norwegian mainland where analysis of the data to detect existing cracks and their appropriate size will be conducted. The project is in the formative stage and plans envision an at-sea test of the system on a North Sea platform in the summer of 1984. (Ocean Industry, Feb., 1982)

7.2.2.f NDE Round Robin

This program is being conducted by Mega Engineering, Silver Spring, Maryland, with support from the USGS and the Office of Naval Research. Its objective is to determine the applicability of several NDE techniques for determining the structural integrity of fixed offshore platforms. Mega Engineering is serving as a neutral agent for the program to independently evaluate the several NDE techniques for detecting offshore structural failures. Several damage and nondamage situations have been devised for a model of an offshore structure. For each situation, the NDE techniques have been applied to determine if damage has occurred and, if so, the location and extent of the damage. The round robin testing program was established in order to compare the applicability of newly-devised NDE techniques for structural monitoring and inspection to assist in planning future NDE research.

An initial series of tests was conducted to establish baseline data for each NDE method. The researchers, or advocates, were permitted to see the models and to adjust their particular instrumentation only for purposes of obtaining this baseline data. The intent of the baseline data is to provide each advocate with a physical description of the tower's performance prior to any damage and against which the data from the damaged mode could be compared. Subsequent monitoring is being performed as a series of blind-mode tests where the testing operations are being accomplished by personnel of the NASA Goddard Space Flight Center, Greenbelt, Md. Using a series of damage scenarios, data are being taken for each of the NDE methods and are given to the corresponding advocates to be analyzed and interpreted. Based on this information, the advocates will attempt to predict the type of damage and its location within the structural model. The results of each advocate's evaluation will be reviewed, and each technique will then be ranked as to its ability to predict and locate damage.

As of November, 1981, test results were obtained for four failure scenarios. This information has been given to the advocates who will analyze the data. The nature and extent of further testing within the program will depend upon their findings. (Dame, 1981)

7.3.1 Vehicles

7.3.1.a EAVE-West and EAVE-East

These programs, EAVE (Experimental Autonomous Vehicle)-West and EAVE-East are being conducted by the Naval Ocean Systems Center, San Diego, LA and the University of New Hampshire, respectively. The objective is to develop the technology for underwater inspections of pipelines and structures by unmanned, free-swimming vehicles. At NOSC, an open-frame torpedolike submersible has been

constructed as a test bed to study magnetic navigation and optical fiber communications. This vehicle is powered by lead-acid batteries which, together with electronics, are located within the frame. Twin propellers are located aft, and a vertical propeller amidships, between synctactic foam buoyancy blocks, provide propulsion for the vehicle. The UNH test bed is roundish in configuration and able to propel itself in any direction. This test bed has twin electrical thrusters on three orthogonal axes and is controlled by electronic equipment located in boxes which are mounted upon the bottom frame. Just below that frame is a ring upon which, for purposes of navigation, 12 equally spaced acoustic sensors are mounted. At the very top are two syntactic foam buoyancy cylinders.

Because future inspection tasks will require more than a stop-and-look capability, man-machine relationship studies are being carried out so that a submersible will be able to perform certain manual tasks such as structural joint cleaning and instrument placement. These studies are being sponsored by the Engineering Psychology Program of the Office of Naval Research. This technology development program has progressed to a point where both the NOSC and the UNH test beds have been tested in water to perform certain fundamental maneuvers.

The EAVE-West vehicle was designed for use as a testbed to investigate various component technological concepts. The goal is not to derive an optimal vehicle system, but to combine different technologies and observe their relationship to one another. Presently the effort is to determine various areas of artificial intelligence that might be adaptable to upgrade state-of-the-art vehicle technology. An LSI 11/23 has been incorporated into the vehicle for these and other experiments. A fiber optics communication link will be installed on the vehicle. It is a full duplex communication link that will be freely deployed from the vehicle with a pre-twist in an attempt to eliminate the entanglement problem. The 1200 baud serial digital data will be multiplexed on the retrace scan of the uplink TV signal. A dichroic duplexer will be used to transmit down over the same fiber. Both active and passive magnetic techniques have been investigated for providing control information for pipeline navigation of the EAVE-West vehicle. Magnetic sensors were chosen for study because of their promising prospects for detecting and following buried pipelines. Results indicate that active magnetic systems should be pursued, primarily because of their inherently cleaner control signals. Transmitter-receiver systems operating at frequencies near either 40 Hz or 4 kHz have been selected. Intermediate frequencies will be avoided because of possible cancellation of magnetic and eddy current effects. As a result of laboratory testing, detection ranges of about 5 m are estimated for 61 cm (24 in.) diameter pipelines.

An electronics system for automatically following the pipeline has been designed, fabricated, and tested in the laboratory. This system consists of two receiver coils and one transmitter coil positioned beneath the submersible. The electronics is composed of two receiver cards and one transmitter card. The transmitter sends out a CW signal at 800 Hz which induces a signal in the pipeline. The receiver coils then pick up, filter, and amplify the signal with automatic gain control circuitry. The signal is sampled in a manner to produce sine and cosine functions which can then be squared and added to eliminate any phase dependency of the received signal. The second receiver card, consisting of a dedicated 8085 microprocessor, actually performs the squaring and addition functions as well as providing a time average of up to 200 samples. The vehicle uses this information to automatically acquire and follow a pipeline even when the pipeline is buried.

A manipulator arm has been designed and fabricated for the vehicle and man-machine studies for its use are being conducted in conjunction with the Engineering Psychology Program of the Office of Naval Research, as previously mentioned.

The early (1977-1979) EAVE-East development task was to design a vehicle-based sensor system capable of detecting an exposed pipeline, and to so control the vehicle that it may acquire and follow the pipeline. A simple computer system was constructed to accept the inputs of twelve acoustic ranging sensors and to employ them in a coarse pattern recognition system to generate steering information and altitude. In 1979 the EAVE-East vehicle successfully acquired and followed a bottom pipeline.

In 1979 to 1982 UNH developed a system, called Structural Inspection Mission System (SIMS), which has evolved into a three-year task. The vehicle, essentially identical to EAVE East, has been given the task of examining a specified underwater structure. Placed in the water up to 100 m away, it homes in on a structure-mounted transducer until the range is approximately 40 m. A three-transponder navigation system in the region near the structure, plus a pressure gauge, permit obtaining a high precision x, y, z position fix. The vehicle is then to penetrate within the structure, to transit through it to a "work station" where it performs the simple task of photographing a target. It then retraces its path through the three-dimensional maze, to return to its launching position.

A high-resolution acoustic navigation system was developed and the mission defined in the computer's terms. The computer's task was to examine the structure and then define safe passage areas within . Although a very simple structure (i.e., a cube) was used, the methods developed could be applied to a more complex structure.

A computer system composed of 3M-6100s was developed. Each one was dedicated to specific tasks: controlling the mission; controlling the vehicle's thrusters; and controlling navigation. Each computer talks to the main computer, which has the mission algorithm and acquires system parameters, such as, temperature of the compass, heading, and depth. In effect, a distributive processing scheme containing specific components was developed which perform well-defined tasks. A modern microprocessor, the Motorola 68000 system, is being developed to extend the system capacity.

Tests of these systems are underway at Lake Winnipesaukee, NH and include evaluation of the navigation systems, the command computer, and mission algorithm. The Interprocessor system and the communication philosophy are both completed and working. The first performance of the above mission was in October of 1981.

In 1983 UNH will attempt to quantify errors in the navigation system. They will also be looking for possible errors in the vehicle's control system, including, in part, an analysis of the dynamics of EAVE East and the design of a control system that will take advantage of this information.

Another area which will be examined is visual imaging. Ultimately, the goal is to transmit real-time TV through the water, but, because of the limitation of the communication channel, it is obviously necessary to be "smart" on both ends. Data compression in this respect is unavoidable. The feasibility of

dealing with this through bandwidth compression has been investigated. A CCD camera was obtained to test a bandwidth compression algorithm on actual underwater imaging. This algorithm can be implemented on a microcomputer, and it appears that compression ratios on the order of 20 to 30 are possible. UNH is presently modeling this algorithm and, once it is working, they will investigate the possibility of putting the digitizer and frame-grabber together to implement the algorithm on a 68,000 CPU. On another 68000 system they will attempt to reconstruct the image in a remote operator's monitor to permit a qualitative comparison of the image begun with and the one they finished with.

A more detailed account of the EAVE-West program and vehicle can be found in Heckman (1980) and the EAVE-East vehicle in Glynn and Blidberg (1981).

7.3.1.b Foundation Mattress Inspection System

The Dutch firm NeCOS (International Navigational Aids B.V.O) has designed a vehicle whose main task is to inspect and determine the condition of foundation mattresses after they have been positioned on the seabed and to detect the presence and thickness of sand on the mattress surface. In view of the utilization of protective sand barriers on many of the artificial islands in the Arctic, it is believed that one or several aspects of this vehicle may have Arctic application.

The inspection system consists basically of inspection sensors mounted on a seabed crawler and a control and monitoring center on board a support vessel. The operation of the inspection system, which will extend over a period of two to three years, is integrated in the working cycles of construction vessels. Among them a mattress laying pontoon and a pier lifting barge. The system operates in a depth of 30-50 meters and work was expected to start in May 1982. The main inspection sensors are six television cameras, fitted with especially designed perspex lenses and four high frequency acoustic transducers, in order to detect a sand thickness with a resolution of 0.5 cm. The underwater visibility in the Eastern Scheldt is sometimes less than 10 cm; thus explaining the choice of perspex lenses acting as a clear vision unit. Data from the inspection sensors is transferred through the umbilical to the surface and processed in real time as well as off line by means of a video-processor and a minicomputer. The crawler has track and wheel drive; either can be selected during operational use to avoid damage to the mattresses while turning. The choice of a seabed crawler was dictated by the prevailing strong currents and by the fact that the targets are on the seabed. (Engels and Huis in't Veld, 1982)

7.3.1.c Marine Maintenance Inspection Machine

The Marine Maintenance Inspection Machine (MMIM) is jointly funded by BP, the UK Department of Energy and Sonarmarine Ltd. It is a deepwater ROV for platform inspection, designed by Sonarmarine Ltd. and built by Slingsby Engineering Ltd. The design philosophy is based on experience gained in the North Sea and it is envisaged that detailed NDE work can be carried out from an offshore structure without the seasonal limitations normally encountered. A number of unique features have been designed into the vehicle, including its shape and winch-garage configuration. Vehicle construction began in July 1979 and trials are now underway.

The design of the MMIM system is based on a number of common ROV failings: system unreliability; umbilical entanglement and damage and inability to gain

access to nodes and lack of dexterity. To overcome these failings the system incorporates the following characteristics:

Unreliability:

-utilizes well tried and proven equipment, where possible. Trials of sufficient length will be conducted on new and unproven equipment to establish its reliability

Umbilical Entanglement:

-the thrusters and their control system are thoroughly reliable and assure that sufficient thruster power is available to aid getting out of confined areas.

-a vehicle garage is used to help getting through the splash zone quickly, and when attached to the structure close to the worksite (by limpets) it provides a suitable haven from which the vehicle can operate.

-the diameter of the umbilical has been reduced thus reducing drag

-all-round vision (a capability for 5 CCTV has been provided) allows the umbilical position to be monitored during the operation.

Umbilical Damage

-a garage/vehicle combination has been designed which can be powered to a position on the outer-face of the structure close to the worksite where it can be attached. This also provides a suitable junction to reduce the umbilical size.

-a vehicle-borne winch has been incorporated which has two advantages: The umbilical is not dragged by the vehicle across sharp cutting edges where damage usually occurs and, if the umbilical does become snagged, the vehicle can continue paying out the umbilical, turn and free itself by using its manipulators.

Nodal Access and Lack of Dexterity

-Models of nodes were built and the optimum vehicle shape decided upon. Also by using the models, the manipulator design was confirmed. It was also decided that a trim system which would allow the vehicle to trim through 30° should be included and suction limpets which would allow the vehicle to be attached at the worksite should also be incorporated.

The MMIM vehicle/garage assembly is some 5 m LOA and weights approximately 5 tonnes. The vehicle is faired for damage protection and to improve the hydrodynamic profile, it has a surface speed of 3 knots and can operate to 400 m depth. A detailed description of the system's design, capabilities and equipment unit is given by Watt (1980).

7.3.1.d ARGYRONETE

Development of the ARGYRONETE began in 1967 and was halted in 1972. As of February 1982 the Marseille-based Comex SA decided to purchase the equipment developed (the vehicle was about 2/3rds developed when construction halted) and complete the vehicle. Design goals are to develop a 600 m depth vehicle with diver lockout capability to 300 m. The 28 m long, 250 tonne ARGYRONETE will carry 10 people (including 4 divers in saturation), have a range of 450 km and an endurance of 14 days. Electrical power will be provided by a closed-cycle diesel or the Stirling engine, both of which have seen considerable development activity in recent years. The vehicle will be used as a test system for such new energy packages and for new submersible inspection/repair techniques. Reportedly, Comex anticipates commencing a two-year fabrication period by the end of 1982 and a one-year sea trial period thereafter.

7.3.1.e The PHOENIX Program

The PHOENIX Program is being conducted by Sub Sea Oil Services S.p.A., Milan, and includes the development and fabrication of the two submersibles and one submarine, all powered by a closed-cycle diesel engines, developed by SSOS, for short, medium and long-range operations respectively.

The PH-1350, launched in 1981, is a short-range submersible capable of operating in conjunction with a saturation system installed on board the support vessel. The maximum lock-out capability is 500 m; the maximum attainable depth is 1000 m. Its operating range is 400 km in the submerged condition plus 400 km on the surface, plus 24 hours continuous lock-out service with the submersible sitting on the seabed. A minimum survival time of 72 hours is provided in terms of heat, oxygen, carbon monoxide scrubbing, oxyhelium mixture supply, water, food and waste bags. The crew will include a maximum number of 4 pilots/operators/surveyors in the atmospheric compartment, 4 divers in routine lock-out conditions or 10 saturation divers in emergency rescue conditions in the hyperbaric compartment.

The medium range submersible will not differ substantially from the PH-1350 except that it will have a greater range, with a higher power rating from two closed-cycle diesel engines. The lock-out diving capability of this class will be to 500 m with 11 saturated divers while the maximum depth attainable by the vehicle at atmospheric pressure will be 2000m, with 4 to 6 non-diving personnel. The main difference in this vehicle will be its greater range in total saturation. No hyperbaric equipment will be kept on board the supporting surface craft. The operating range of vehicles belonging to this class will be 250 miles at maximum speed 14 knots. Submerged duration will be 10 days.

The final stage of the project will develop a "submarine" type vehicle capable of working offshore with a 800 km navigation range and 24 days saturation endurance. The maximum crew will be 22 persons. The survival time will be 72 hours also for this class and the submarine will be tended at all times, for safety reasons, by a surface craft such as a tug or supply vessel. Maximum lock-out diving capability will be 500 meters, whereas in the atmospheric mode this submersible will be able to reach 2000 meters depth.

The PH range of submersibles has the potential to fulfill maintenance and routine inspection requirements of a complete offshore field with many fixed

structures and pipelines. They, like ARGYRONETE, may find application to Arctic inspection problems. (E. Marino, SSOS, personal communication)

8.0 SUMMARY AND RECOMMENDED RESEARCH

8.1 SUMMARY

8.1.1 Production

The Arctic Ocean, in particular the Canadian and U.S. Beaufort Sea areas, have witnessed a tremendous surge in the exploration for offshore oil and natural gas. While exploratory drilling began in the 1950s, it was not until the seventies that significant exploration began. Today some 16 oil companies have drilled--and continue to drill--in the Beaufort Sea. Commercial finds of oil and gas have been discovered, but there is, as yet, no production from these wells. The consensus of opinion among most operators is that production from the Arctic offshore will commence by the mid-eighties, and reach full strength by the end of this decade. Adherence to this schedule is not necessarily governed by the needed technological breakthroughs, but more so by economic, political, and environmental considerations.

Exploratory drilling in the Arctic Ocean is being conducted from a variety of platforms: artificial gravel islands, drillships, man-made ice islands, grounded natural ice islands and artificially thickened sea ice. In terms of ocean depths Beaufort drilling is relatively modest. Ice island drilling is being conducted in about 3 m. depth, artificial gravel islands in 5 to upwards of 19 m. depth and drillships in waters of 230 and 262 m. depth.

8.1.2 Platforms

At this time there is only one production platform offshore, a wet, subsea production system, which is non-operative. Production platform designs and concepts are many and varied and include platforms constructed in the Arctic (artificial gravel islands, caisson-retained islands, ice islands and underground tunnels) and those which are constructed elsewhere and brought to the Arctic (barges, cones and monocones, floating caissons, and wet and dry subsea completion systems). Likewise, there are a variety of concepts for Arctic oil and gas loading terminals and pipeline installation/protection techniques. It is likely, when production does begin in earnest, that no one platform or concept will satisfy all Arctic conditions. Instead, one can anticipate a variety of structures designed to satisfy a particular environment in, say, the landfast ice zone, the shear zone and the permanent ice cap zone. Undersea pipelining is also envisioned as taking several forms. Some conceive laying the pipe in tunnels for protection against ice gouging; others envision burying the pipe with an adequate thickness of overburden. While in areas too deep for ice damage the pipe can be laid unburied on the seafloor. Indeed, there is even some question as to the utilization of pipelines vs surface tankers designed for ice breaking which may prove more economical.

8.1.3 Inspection Requirements

Of those nations which border the Arctic Ocean (the U.S., Canada, Greenland, Norway and the USSR), only the U.S. and Norway have undersea inspection requirements for pipelines and structures. Both Canada and Greenland have written inspection requirements, but neither are in effect at this time. U.S. and Norwegian inspection requirements can be met in the Arctic with one exception.

This being a U.S. requirement that pipelines which are suspected of leaking be monitored by aircraft overflights of the pipeline route to look for surface evidence of leakage. An ice cover negates this approach. The offshore operators have imposed their own inspection requirements which, although they do not specifically address the Arctic, can be met with few exceptions also. The exceptions lie mainly in pipeline inspection where conventional techniques may not be able to monitor, for example, the cathodic protection system when the pipe is buried some 5 or 6 m below the overburden.

8.1.4 The Offshore Environment

The Arctic climate is undoubtedly the most rigorous area in the world where oil and gas development is occurring. Wind chill factors of -45°C and almost perennial snow and ice produce surface conditions which will virtually always preclude "routine" operations. From an oceanographic operating point of view, however, the Arctic is not any more inhospitable than other areas of the world (once the ice has been penetrated or removed), and in certain respects less so than some. Water temperatures, although below freezing, are not an insurmountable obstacle to underwater operations. Currents are much less than in the North Sea. Underwater visibility is generally good to excellent. Sea states are generally less than more southerly latitudes. The primary obstacle to underwater operations is ice.

Ice has two detrimental effects: 1) it must be removed for certain types of inspection and 2) its daily migration rate in some areas precludes utilization of a wide variety of underwater techniques which are dependent upon an umbilical for power, breathing gasses, data telemetry, command/control, etc. A third effect of ice is its ability to gouge deep trenchs in the sediment which, in the process of doing such, may also damage or destroy a subsea pipeline. For this reason some pipelines may require burial to depths beyond which conventional inspection techniques will not be effective.

The obvious alternative to the ice problem is to work during the "ice free" season. This season is, depending upon the source, from as little as four weeks in some areas up to as much as three months in others. Regardless of its tenure, the ice free season leaves a very short operating window for inspection. Particularly since the inspection chores will have to compete for platform availability with other maintenance, repair and logistic activities.

8.1.5 NDE Equipment and Deployment

Underwater NDE tools and devices are various and consist of visual and photo/optical devices, magnetic particle and magnetographic inspection, ultrasonic devices for thickness measurements and flaw detection, remote and direct cathodic potential monitors, tomographic techniques, radiography and intelligent pipeline pigs. None of these devices are precluded from Arctic application due to environmental constraints. Operational employment, however, could prove difficult and, in some instances, impossible. While there are many reservations regarding the effectiveness and the data obtained from specific NDE devices, in the main they are acceptable to certifying authorities, although improvements would be welcome. Pipeline pigging, owing to the potential depth of pipe burial, the ice cover and the short weather window, will assume a greater potential significance in Arctic inspection than it does in other ice free areas. The primary NDE problem seems to reside in the implications of the data. That is, what specifically does it mean in terms of platform integrity. This problem is beyond the

question of NDE, but more in the realm of basic material properties and characteristics.

Deployment techniques, such as divers (saturated and non-saturated), ROVs and manned submersibles can be deployed in the Arctic as they are elsewhere in the world, but are limited for certain types of inspection to the ice free season. The only devices which can operate year-round are untethered submersibles, autonomous ROVs and pipeline pigs. Limited electrical power and reliability/human safety considerations of present manned submersibles somewhat dampen the enthusiasm for application of these vehicles. Autonomous vehicles are still in the development stage and present pipeline pigs do not provide all the capabilities required to meet some inspection criteria.

8.1.6 Current Arctic NDE Research and Development

While acknowledging the need for regular and thorough underwater inspection of Arctic structures and pipelines, offshore oil and gas operators are presently more involved with developing exploratory drilling techniques and production facilities than they are developing inspection techniques. Until design concepts are firmed, addressing the inspection problem is considered premature at this time.

There are, nonetheless, several R&D projects which are designed for Arctic application. While these projects are not NDE oriented, some of the capabilities which are developed will have application. They include development of underwater, 1-atmosphere welding/inspection chambers, long-duration saturation diving habitats for maintenance and repair and autonomous vehicles for underice bottom and ice keel profiling.

The majority of current NDE R&D projects are not directed specifically for Arctic application. But many of the objectives, when attained, can find application therein. This work, conducted on the part of industry, government and academia, cover the spectrum of NDE instrument and tools, techniques,and deployment capabilities. Of particular interest to Arctic inspection are several programs including: flooded member detection; pipeline leak detection and structural vibration analysis using global and local mode techniques. These projects are identified because, if successful, they could reduce the inspection time required for detailed (i.e., crack, pitting, etc.) NDE and, thereby, accommodate the short weather window. Other research programs with Arctic significance are related to autonomous vehicle development and the development of long power duration, large manned submersibles, both of which may permit inspection to be conducted underice. Pipeline pig development projects are being conducted which also permit year-round inspection capabilities, but these are all industrial developments, the details of which are held proprietary and, consequently, their application to Arctic pipeline problems cannot be assessed.

8.2 RECOMMENDED RESEARCH

The following recommendations for research are those which this study have identified based on conceptual designs for Arctic structures and pipelines and for equipment employed elsewhere than in the Arctic. As North Sea inspection experience has revealed, there will be problems inherent with using underwater equipment

designed for use in one environment (such as the Gulf of Mexico) and employing it in a quite different environment--the North Sea. Until the NDE equipment described in the foregoing section has been used in the Arctic, one can only speculate on its performance. Undoubtedly, problems will arise which are unique to the Arctic, but cannot be foreseen at present. A second factor which tempers the recommended research is the preliminary stage at which oil and gas production now stands in the Arctic. As was shown in Chapter 3, there are numerous design concepts for Arctic production platforms and the ultimate solution to pipeline protection, none of which appear to exceed the other at this point, and all of which may find utilization ine one area or another of the Arctic Ocean. It is--like inspection requirements themselves--somewhat premature to be recommending specific research efforts for structures which have not yet been selected. A third tempering circumstance is the number of questions regarding the Arctic Ocean itself, specifically the ice effects and permafrost, which must be resolved before structural designs and pipeline burial techniques can be finalized.

The foregoing qualifications, therefore, delineate relatively well-defined boundaries within which recommendations for research can be made if they are to find application to Arctic structures in general and partially understood environmental conditions. Nonetheless, there are known conditions in the Arctic which must be contended with in any design, and for which only a very limited number of options are available. It is a fact that the Arctic weather window for underwater inspection is and will continue to be shorter than any other area in the world oceans. This limitation forces the inspection program to be performed at greater speed than in other ocean areas. It is also known that the ice cap migrates, as much as 24 km/day, which precludes utilization of conventional inspection techniques which rely upon a surface connected umbilical, and encourages development of techniques which do not use an umbilical. Investigations have also revealed that ice ridges and ice rafts gouge into the bottom as much as 5 m to 6 m depth. This phenomenon practically ensures that pipelines within the ice gouging areas must be buried to at least the depths of observed gouging. This, in turn, places the pipe at depths beneath the bottom which exceed the capabilities of present external pipeline inspection techniques and encourages development of intelligent pipeline pigs. We also know that it is presently impossible to visually monitor the seasurface over a pipeline route for signs of leakage when the route is capped with ice. To satisfy this requirement, techniques other than visual surveillance from aircraft must be developed. The foregoing realities of the Arctic environment are those upon which the following recommenations are based.

8.2.1 Short Weather Window

Several techniques are being investigated and have been described which seek to provide a rapid reconnaissance of a structure to identify areas (i.e., members) on the structure which require detailed NDE. Development of these techniques should be pursued because, if successful, they will reduce the time required for deployment of divers, ROVs, etc., and, consequently, accommodate the brief period of Arctic ice-free conditions which produce competition for access to the platform by a variety of equally necessary support services. Three areas of research appear to provide a possible solution to this problem: vibration monitoring (local mode); acoustic emission monitoring, and acoustic surveillance for flooded members.

8.2.1.a Vibration Monitoring

Although vibration monitoring in the global mode method does not appear to have lived up to its earlier expectations, monitoring by the local mode method (as described in sections 7.2.2.d and 7.2.2.e) appears to have merit. This technique

should be investigated to determine the extent to which it can be relied upon and the limits to what it can detect regarding a member's integrity. Once such limits have been identified and a confidence level established, the level of effort for development, improvement or modification of present NDE devices (c-p monitoring, mpi, ultrasonics, etc.) can be established.

8.2.1.b Acoustic Emission Monitoring

Earlier attempts at acoustic emission monitoring were limited by a number of factors, one such being the permanent attachment of transducers/hydrophones to the structure. Current acoustic monitoring techniques by Kockums and the Norwegian Institute of Technology do not envision permanent emplacement of transducers on the structure, but, instead, only to immerse an array of sensors by cable for the period of monitoring. This approach is advantageous for reasons of expediency, cost and dependability. Research into this area, like vibration monitoring, should seek to establish the limits of the technique and its applicability to Arctic structures as preliminary inspection reconnaissance techniques.

8.2.1.c Flooded Member Detection

This technique, as described in section 7.2.2.a, has, as one of its shortcomings, the distinct disadvantage that it does not forewarn of a problem, but the existence of one. In this respect it falls somewhat short of an ideal inspection technique, but does have application since it is, in concept, a rapid means of identifying a faulty member. In this role it would seem to be the next step after acoustic emission or vibration monitoring have identified that there has been a fundamental change in a member's material properties. In essence, the technique, if successful, quickly establishes the worst case condition: that a member has cracked. Conversely, it also can establish that a crack has not fully penetrated the member, but is surficial in nature. This knowledge can be used in selecting the next type of NDE procedure and the pace at which it need be conducted. The technique should be investigated to determine its reliability and its adaptability to deployment from an ROV.

8.2.2 Ice Cap Migration and Cover

The simple presence of an ice cover, as discussed above, precludes satisfying the legal requirement for visual surveillance of the sea surface over a pipeline suspected of leaking. Migration of the ice cap precludes utilization of vehicles or platforms which depend upon a surface-connected umbilical for operation and data telemetry. Two alternatives are available: a manned, untethered submersible or an autonomous ROV. The manned submersible, although an attractive option, carries with it the concern for human safety, and because of this concern, it is, by necessity, a last choice for independent underice operations. The autonomous ROV is a recommended alternative for inspection of unburied or shallowly-buried (less than 1 m) pipelines.

8.2.2.a Autonomous ROV

Research and development of autonomous ROVs such as being conducted in the EAVE West and East programs and the ARCs project should be continued. Development should concentrate within the following areas:

- improved energy source to permit continuous operations for a minimum of 24 hours

-vehicle positioning to at least ±3 m at any point on the pipeline
-magnetic pipeline following capability, to hold the vehicle within optical viewing range (1 to 3 m) of the pipeline
-instrumentation development to include:

video observation and tape storage
stereophotogrammetic camera system
leak detection sensors (for oil and gas)
remote c-p monitoring capability (current density field)
pipeline insulation integrity monitoring (e.g., infrared technique, thermal measurements)

It is tempting to envision an autonomous vehicle which can relay the information it is gathering back to the surface in real-time. This is an attractive goal, but in light of present and foreseeable manipulative techniques, it is unrealistic, since intervention by a diver, tethered ROV or manned vehicle will be required to correct whatever defect or problem is discovered. Near-future autonomous ROV capabilities for Arctic pipeline inspections can be satisfied by a vehicle that can automatically follow a pipeline, record the data onboard and reconstruct the data's position to within ±3 m on the pipeline. In essence, the autonomous vehicle's role is envisioned to resemble that of the techniques recommended for research in section 8.2.1: a general reconnaissance to determine the need for detailed NDE or maintenance/repair.

8.2.3 Deeply Buried Pipelines

8.2.3.a Intelligent Pipeline Pigs

The most practical solution to inspection of pipelines buried 5 or 6m below the sea bottom is pigging. In view of the fact that virtually all pipeline inspection is conducted to monitor a pipeline's integrity, it would seem that pigging is preferred over all other techniques since it looks at the pipe from within--where corrosion, pitting and cracking is most likely to take place in an operating pipeline. External inspection of unburied pipelines through conventional techniques attempt to identify mechanical damage brought about by trawlers or anchors, the existence of suspended sections, the effectiveness of the c-p system and spalling or inadvertent removal of the concrete coating. Deeply buried Arctic pipelines will not be subject to any of these problems, excepting c-p monitoring, once they have been backfilled. Consequently, the major pipeline problems are anticipated to originate from internal, rather than external, factors.

To the extent determinable, the capability and limitations of current intelligent pipeline pigs have been identified in sections 5.2 and 6.4, respectively. All present research and development in intelligent pigs is being conducted by activities who will offer these services in a competitive market. These activities are reluctant to divulge their objectives and techniques in order not to lose whatever competitive edge they might have. Consequently, research and development is taking place which was not made available to this study. It is therefore impossible to avoid recommending research which may not already be taking place in one of the industrial activities.

Several areas of pigging inadequacies have been identified which are recommended for research; these include

-Measurement inaccuracies due to mandrel marks
-Pre-knowledge of each pipeline segment's wall thickness

-Pitting depth measurement limitations
-Laborious procedures for grading and analyzing logs.
-False readings due to foreign metallic objects.
-Inability to detect defects less than 2.5 cm from welds
-Inability to confidently measure longitudinal defects less than 2.54 cm width

Arctic pipeline inspection requires research into two other areas where pigging capabilities may be found lacking: c-p monitoring and inspection of thermal insulating material.

It is not certain at present what type of cathodic protection system for deeply buried pipelines will be utilized: impressed current systems or sacrificial anodes. Monitoring the effectiveness of impressed current systems is a relatively simple task which can be accomplished without the need of pigs or ROVs. Techniques for monitoring a sacrificial anode bracelet, as discussed in an earlier section, have been developed for unburied pipelines and, reportedly, for pipelines buried to depths from 1 m to 3 m (maximum). No techniques, as far as can be determined, have been developed for monitoring a sacrificial anode from the interior of a pipe. Such a technique must be developed if sacrificial anodes are to be used on deeply buried pipelines.

The need for some form of thermal insulation around pipelines buried within permafrost zones seems assured. At present, the nature and configuration of such insulation is uncertain. Regardless of the type of insulation finally chosen, it will need be inspected periodically to assure that it is performing effectively. Research into pig sensors which can perform such monitoring should be pursued apace with development of the insulating materials.

Intelligent pigs provide a unique tool for Arctic pipeline inspection, particularly since they are the only devices which can inspect deeply buried pipelines, and they can also be deployed year-round regardless of the ice cover. At the very least, industrial activities in development of pigging capabilities should be closely monitored to determine whether or not they will satisfy unique, near-future Arctic requirements.

8.2.4 Overall Inspection Scenarios

8.2.4.a NDE Round Robin

Section 7.2.2.f. identified the many uncertainties and, in some instances, failures in present NDE techniques. Comparative tests of these techniques, such as described in section 6.1, were conducted by industrial operators and the detailed results are proprietary to the company conducting the tests. The results of this study strongly endorse the pursuit of the NDE Round Robin program. New NDE techniques are being avidly developed nationally and internationally. The developers or advocates of these techniques consider them improvements over present techniques. Pride of ownership may encourage claims for performance levels somewhat in excess of the devices' actual capabilities. Operators of platforms, the ultimate customer of these new techniques, do not generally subject them to rigorous test and evaluation. Government activities in a position to impose inspection requirements are generally even less aware of the sometimes wide margin between advertized capabilities and demonstrated capabilities. Programs of the Round Robin variety serve a valuable function by objectively discriminating fact from fancy and making the results available to the broad community who must pass judgment and write requirements based on the effectiveness and practicality of available NDE techniques.

8.2.4.b Artificial Island Inspection

Patterson et al (1982) described the utilization of side scan sonar to monitor the position and integrity of sand bags used for the underwater protection of an artificial island. The side scan records are in the form of a strip chart upon which three-dimensional facsimiles of the bottom (i.e., protection) are impressed. Presently, these facsimiles are manually compared against the drawings showing initial emplacement of the sand bags. This is a laborious chore which, by nature, becomes less accurate the longer the comparer works. In the final analysis, the task is ultimately one of pattern recognition and comparison. In view of the increasing activity in the area of pattern recognition, it would seem that this task would be more rapidly and accurately accomplished through application of these techniques. Research into the potential for adopting such techniques in regards to inspection of undersea rampart protection schemes is recommended.

8.2.4.c Structure Inspection Techniques

One of the unique features of Arctic structure design concepts is the enclosure of supporting members, risers, anodes and other critical equipment within the shell or column providing protection from the ice. This concept, apparently, eliminates many of the current problems attendent underwater inspection (i.e., sea state, currents, ice presence). It is beyond the scope of this study to perform an in-depth analysis of this observation and particularly so since the final design of many of the concepts have not been reached. If, as it appears, inspections can be conducted from within the structure, rather than from without, this will have considerable impact on the extent, timing and nature of the inpection. It is recommended that production platform designs which appear most likely to find application be carefully examined to determine the feasibility of conducting inspection of critical components inside the protective shell. Further, investigation should look at the feasibility for inspection of the shell itself from the inside.

APPENDIX I

NDE DEVICE SPECIFICATIONS

OSEL GROUP
MAGNETIC PARTICLE INSPECTION UNIT

SPECIFICATIONS

Sub Sea Unit

Prods: 1500 amps a.c. or d.c.
Adjustable spacing of electrodes with lead or copper tips
Variable output with demagnetising facility
Open circuit voltage of 8 volts.

Coil or Cable: 55 feet continuous loop, 1000 amps a.c. or d.c., 5 volts.
Duty cycle of 5 mins. continuous, 5 mins. off.
Air driven, agitation by electric paddle, capacity 10 litres

Weight in Air:	78 kg
Weight in Water:	40 kg
Length:	647 mm
Width:	317 mm
Height:	457 mm

Lamp

220 volt x 125 watt output at 0.5 m in excess of 250 lux.
Detachable for dispenser.

Weight in Air:	2 kg
Weight in Water:	1 kg
Length:	230 mm
Width:	93 mm
Height:	200 mm

Surface Control

Digital output current meter
Earth circuit fault indicator remote control with current readout, full earth leakage protection magnetizing unit operating indicator.

Weight:	14 kg
Width:	527 mm
Height:	305 mm
Depth:	362 mm

Isolation Transformer

Length:	550 mm
Width:	550 mm
Height:	220 mm
Weight:	50 kg

Optional Extras

12" cable reel and stand for umbilicals less than 100 meters.
27" cable reel and stand for umbilicals over 100 meters

The complete OSEL M.P.I. system is rated to 305 meters (1,000 ft.)

CNS ELECTRONICS, LTD.
FeDEPTH METER

SPECIFICATIONS

Dimensions	343 mm x 292 mm x 128 mm (13½" x 11½" x 5")
Weight	5.4 Kg (11.5 lbs.)
Power Source	Rechargable Storage Battery with built-in charger, 110-125 V/200 - 250 V. 50-60 Hz
Battery Life	9 hours continuous operation after full discharge/charge cycle Recharge time 3½ hours
Operating Temperature Range	$-1^{o}C$ to $43^{o}C$
Storage Temperature Range	$-18^{o}C$ to $60^{o}C$
Detection Range, 16mm dia. bar	Max. 200 mm, Min. 6 mm with spacer
Bar Size	5 Calibrated ranges, 10, 16, 25, 32 and 40 mm.
Bar Size Measurement Accuracy	± 3 mm or $\pm 1/8$"

ROXBY ENGINEERING INTERNATIONAL LTD.
BATHYCORROMETER MARK V

DESCRIPTION

The Bathycorrometer Mark V provides a means of ascertaining the corrosion/protection condition of any submerged metallic structure; pipelines, jetties, drilling rigs, production platforms and ship's hulls. A silver/silver chloride reference cell is used which is 5 cm from the surface being measured to provide localized measurements. More average potential measurements can be obtained by using the extension lead supplied.

The potential provided by the reference is displayed on a 3½ digit 15 mm liquid crystal display, which, combined with Betalight back illumination, provides the ability to read in any ambient light condition. If required, an L.E.D. display can be supplied. A 4 pin underwater output socket in the base of the handle provides a means of recharging the battery, separately testing the half cell and an output for either remote readout and/or recorder operation.

If simultaneous surface monitoring is required, the Mark V unit achieves this by the addition of a surface readout module and 2 core underwater cable, or if spare cores are available, an existing umbilical. A 4 - 20 milliamp signal loop transmits the data to the surface or other remote locations. This overcomes interference from, or to, adjacent equipment, other umbilical signal wires, and cable attenuation problems.

If diver surveillance by closed circuit television is used a Camfax Interface Module, enables the reading from the Bathycorrometer Mark V to be displayed in digital from, on a standard V.D.U. Consul. The information can also be recorded on V.C.R and V.T.R equipment and a 4-20 milliamp signal is available for use with data loggers or any other conventional recording equipment.

SPECIFICATIONS

Dimensions:	10 cm diameter, 27.5 cm long Handle 12.5 cm long, 4 cm diameter
Weight in air:	2.5 kg
Weight in sea water:	.85 kg
Meter Input Impedence:	5 Megohm per volt
Overall accuracy:	±5 Millivolts
Maximum depth:	305 m (1000 ft.)
Carrying case:	44 x 31 x 14 cm

MORGAN BERKELEY & CO., LTD.
RUST READER SUBSEA GUN

SPECIFICATIONS

The bright color pigmented gun body is made of "E" glassfiber spiralled reinforced polyester resin, and the ergonomically designed pistol shape for easy holding was evolved after close discussion with diving operators.

The Silver/Silver Chloride electrode (of the type developed by Morgan Berkeley for NATO warship use) is moulded into the body and detects potential at a fixed 10 cm from the structure surface. This gives a repeatability of about 1 mV when comparing two electrodes in identical conditions, which is a degree of consistency not previously available.

Contact to the structure is by replaceable hardened cone tips of AISI 410 stainless steel, which because of its polarization characteristics does not contribute electrically to the cathode. Cone angles of 30^{o}, 45^{o} and 60^{o} are available to suit different applications. A blunt cone is used for surveying bare metal structures while a more accutely angled tip is used to allow easy penetration coatings.

The discrete, clearly illuminated digital display is accurate to 1 mV giving precise prognosis of corrosion by its highly definitive reproduceability. The integral digital voltmeter is highly stabilized with built-in reference electronics and gives a read-out of $\pm$ 1999 mV. The high internal impedence of the voltmeter means that even a fairly poor contact to the structure will give an accurate reading.

The Nickel/Cadmium batteries which power the gun are located in the handle and are re-charged between a sealing screw at the base of the handle and the contact tip. The batteries give three hours continuous use which can be extended to 24 hours by use of the ring switch, which the diver can operate one handed as it will roll on a sleeve or suit. A re-charging system with intrinsic over-charge control, is built into the carrying case, along with test coupons and spare tips. A lanyard mounting point and a lanyard is supplied with the gun.

Length: 382 mm
Width: 61 mm
Height: 235 mm

CORRINTEC/UK
PIPELINE C-P MONITORING SYSTEM

SPECIFICATIONS

Probe

Overall probe length	850 mm
Length: probe tip to bracket center	730 mm
Length: bracket center to probe end	120 mm
Minimum clearance for cable tail	150 mm
Effective length probe diameter	119 mm
Bracket length from center line	170 mm
Weight in air	5.2 kg
Weight immersed	3.0 kg

Attachment to Submersible

The mounting bracket is bolted to the manipulator arm. The standard bracket provided can be adapted to all types of arms currently in use.

Mechanical Loading of Probe/Bracket During Operation

Maximum axial load	1000 kg
Maximum side load at tip	100 kg

Cabling

An armored cable connecting link is provided; length 5 meters. It mates with the digitizer and is clipped along the manipulator.

REMOTE ELECTRODE

Length	200 mm
Diameter	40 mm
Weight in air	0.70 kg
Weight immersed	0.50 kg

Attachment to Umbilical

The electrode is clipped to the umbilical with disposable nylon clips.

Electrode Cable

Length: 75 meters. A mating plug connects with the digitizer. The cable is taped or clipped to the ROV umbilical cable, attached every meter.

DIGITIZER

Length	420 mm
Diameter	115 mm
Weight in air	4.3 kg
Weight immersed	0.0 kg

Corrintec System - 2

The digitizer is attached to a suitable part of the ROV framework by means of universal brackets.

Connections

A four core cable from the digitizer leads to the ROV umbilical junction box. Two cores are used to transmit the digitized signal.

Power Requirements

12 - 24 volts d.c. 5 watts.

Umbilical Requirements

CORRINTEC requires sole use of one shielded, twisted pair of conductors, or one coaxial cable. The umbilical is to be provided by the diving company.

DATA RECEIVER/MONITOR

Width	330mm
Height	280mm
Depth	465mm
Weight	20kg

Power Supply Requirements

11/115/220/240 V a.c. 50/60 Hz 80 watts.

Connections

Provided with a 3-meter power connection a.c. input cable.

Signal Input

A 3-meter shielded, two core connecting cable is provided. This cable connects to the ships cable running from the junction box on the umbilical winch.

Signal Output

An analog output is provided to allow connection to a video writer. This allows presentation of cathodic protection potentials on the TV monitor.

Signal range 0 to $\pm$ 1.999 volts.

A 3-meter cable is provided for the signal output.

COMPUTER AND INTERFACES

Hewlett Packard 9825

Height	130mm
Width	384mm

Corrintec System - 3

Depth	495mm
Weight	11.8kg

Power Supply Requirements

110/120/220/240 V a.c. 50/60 Hz 200 watts.

Connections

A connecting cable is provided for the a.c. supply. Length: 3 meters.

The connecting cable for the Data Receiver/Monitor is also provided. Length: 2 meters.

OPERATING ENVIRONMENT FOR DATA RECEIVER AND COMPUTER

These equipment must be sited in a clean dry environment.

Temperature range	10 - 30^{o}C
Ambient Humidity	80%

ENVIRONMENTAL DEVICES CORPORATION
TYPE 981 CORROSION DETECTOR

SPECIFICATIONS

Sensor:

Sensor Type:	Ag-Ag Cl
Range:	0-1 volt
Threshold:	1 uV
Number of Sensor Cells:	32
Number of Reference Cells:	1
Sensor Cell Spacing:	logarithmic from center of array

Display:

LED Display:	32 Red & Green LEDs spaced proportionately to sensor cell spacing
Polarity Measurement:	Red LED = +; Green LED = -
LED Display Length:	15.2 cm (6 in.)

Microprocessor:

Type:	RCA 1801 CMOS
Zeroing:	Automatic
Scaling:	Automatic

Power:

Batteries:	Rechargeable Ni Cd

Operating Environment:

Operating Medium:	Salt or brackish water
Operating Temperature Range:	-2^{o} to $+45^{o}C$ ($+28^{o}$ to $113^{o}F$)
Storage Temperature Range:	-34^{o} to $+64^{o}C$ (-29^{o} to $+149^{o}F$)
Maximum Depth:	200 ft.

Instrument Housing:

Material:	PVC plastic
Finish:	Natural/Unpainted
Hardware:	Plastic

Physical Size:

Weight:	5.4 kg (12 lb) in air
Buoyancy:	Neutrally buoyant
Dimensions:	See Dwg. SK A101579-3
Shipping Weight:	20.4 kg (45 lb)
Shipping Crate Dimensions:	60 cm x 30 cm x 30 cm (2" x 1" x 1")

INTERSUB SERVICES
CURRENT DENSITY EQUIPMENT

DESCRIPTION

The Intersub Current Density equipment measures the density of the Cathodic Protection current flowing through the seawater between the anodes and the pipeline. Basically the equipment measures the vertical component of the local current density, i.e., the Cathodic Protection current flowing from the anode into the pipeline.

SPECIFICATIONS

All components of the system exposed to seawater are manufactured from plastic materials to avoid locally induced corrosion currents which could interfere with Cathodic Protection current measurements.

- Resolution: 0.1 mA/m2
- Noise level: ± 0.3 mA/m2
- Measurement range: 1 to 1000 mA/m2
- Time constant: 0.3 sec.
- Measurement rate: 3 per second
- External signal rejection ratio: 40 db
- Calibration level: 50 mA/m2
- Data output: 4BCD digits
- GPIB output compatibility
- Sensor dimensions: Ø 430 mm x 500 mm
- Sensor weight: in air 40 Kgs
  in water: 15 Kgs
- Operating depth: 200 meters
- Other dimensions:
  Panel: L 350 x 1 120 x H 240 mm
  Weight: 10 Kgs

  Remote: L 180 x 1 100 x H 100 mm
  Weight: 2Kgs
- Power requirements: 24 V - 75 VA

APPLICATIONS

The equipment requires no contact with the metal of the pipeline and can be continuously operated along the length of the pipeline by either a manned or unmanned vehicle. Raw data output is the local vertical density that has to be subsequently integrated by computer over pipeline/anode length and corrected for distance, to produce a current output.

The computer analysis of the data obtained during a pipeline inspection provides the following basic information:

1. The status of the cathodic protection system and corrosion conditions along the pipeline based upon: detection of defects such as breakdown of pipeline insulation, missing or defective anodes, abnormal cathodic protection currents/anode consumption.

2. Long term evolution of the cathodic protection afforded to the pipeline based upon: estimation of anode life duration, comparison of adjacent sections, and the observation section by section of the evolution with time of the cathodic protection current demand.

INTERSUB SERVICES
PIPE TRACKING SYSTEM

DESCRIPTION

The Pipe Tracker System detects a buried or an unburied pipeline by inducing eddy currents in the pipe which in turn produce a magnetic field. This field is detected by receiver coils and processed to give the vertical height above the pipe and the lateral distance away from the pipe axis.

SPECIFICATIONS

Principle: Electromagnetic
Coils: one transmitter
two receivers
Vertical Distance:
- to top of 32" pipe: 3m ± 10 cm
- to top of 16" pipe: 2.25m ± 10 cm
- to top of 18" pipe: 1.75m ± 10 cm

Lateral Distance:

to pipe axis for all pipes: 1.5m ± 20 cm

Pipe detected at any angle of crossing. System performance unaffected by any non-magnetic covering

Auto-pilot: tracking ± 1m either side of pipe at 1 knot.

Calibrations:
1. away from pipe: electronic compensation of residual offsets.
2. On pipe: automatic calibration of measured parameters.

Maximum operating depth: 300 meters

Data Output
- Auto-pilot: 1V/meter lateral (filtered)
- Digital: 3 BCD digits lateral
3 BCD digits vertical
- GPIB output compatibility

Dimensions
- Sensor: Ø 140 x L 2000mm
weight: 45 Kgs (in air)
20 Kgs (in water)
- Fiberglass arms (2 in number)
L 660 x H 500 mm
Weight: 15 Kgs
- Panel: L 490 x 1 210 x H 200 mm
- Remote control/display
L 190 x 1 120 x H 100 mm

Power Requirements: 24 VDC - 100 VA

Installation: At least one meter away from any significant or moving metallic mass.

APPLICATIONS

The Pipe Tracker allows a manned or unmanned submersible to detect and track a pipeline even when buried to a depth of 2 to 3 meters below the seabed. Also, when integrated with a pressure sensor and echo sounder through the Data Acquisition System digital recorder it provides the data to produce pipeline trench profiles, depth of burial and the geographical location of the pipe. When integrated with a Current Density System provides the data to integrate the continuous current density curves whether the pipe is buried or not. Operations of the system only require the sensor to be installed away from large or moving metallic masses, and offset compensation to be made outside the pipe when starting the survey.

WELLS-KRAUTKRAMER LTD.
DMU Digital Ultrasonic Wall Thickness Meter

DESCRIPTION

The DMU is derived from the circuitry of the Krautkramer DM2 Wall Thickness Meter and has been re-packaged for underwater operation. It is battery operated, has no external controls and is equipped for one hand operation. Shaped like a torch, the DMU has an integral spring loaded transducer at the front end. The movement of the probe when the instrument is depressed against the test piece switches the instrument on. The DMU is pre-calibrated for steel. A zero facility is provided for adjustment out of the water in a service department by access through the charging socket. If required the instrument can be re-calibrated internally to any material and sound velocity within the standard DM2 range. Standard accessories include a detachable and moveable pistol grip, a lanyard, a battery charger and carrying case.

SPECIFICATIONS

Measuring Range:	3 to 200 mm
Measuring Accuracy:	3 to 100 mm $\pm$0.2 mm 100 to 200 mm $\pm$0.5 mm
Test Material:	Pre-calibrated for steel (5940 m/s) but other materials may be tested by internal adjustment of the instrument.
Display:	Digital LED, 3 figures with additional LED indication of battery state, couplant check and overflow.
Dimensions:	Total length - 31 cm (12 in.) Maximum Diameter - 8 cm (3 in.) - excluding pistol grip
Batteries:	5 rechargeable 1.5V cells
Charging Time:	16 hours
Water Depth:	183 m

REIMER CONSULTANTS
AUTAMAP

SPECIFICATIONS

System A

- Thickness measuring element is a Panametrics 5222 Ultrasonic Thickness Gage (modified) with a contact transducer. The Thickness Gage provides a digital display of the measured thickness suitable for stand-alone operation and for on-line monitoring when in the AUTAMAP console. Simple controls and displays require minimal operator training.
- Measurable thickness range in steel of 0.150" to 2.000" with 0.001" resolution (centimeter or inch output). Measurable thickness range will vary with materials other than steel and with cable length. For optimum accuracy, paint on the side facing the transducer must be removed or its thickness determined and typed into the computer memory.
- System is entirely digital. No operator interpretation of a CRT display is required. System calibration is straightforward and stable.
- Data interpretation, when necessary, is performed on the hard copy print-outs which remain available for later re-examination.

System B

- Thickness measuring element is a Nortec NDT-131D Digital Ultrascope with a stand-off transducer. The Ultrascope provides a CRT display of the echoes received and a digital display of the measured thickness. The Ultrascope is a general purpose ultrasonic NDT instrument. It provides substantially more measurement versatility than does the thickness measuring element used in System A. However, it also requires greater operator skill and training.
- Measurable thickness range in steel is 0.020" to 250.0" with 1% resolution. Measurable thickness range will vary with materials other than steel. The presence of paint and other uniform surface coatings of unknown thickness normally does not affect obtainable accuracy.
- CRT display permits measurements to be made in unusually difficult circumstances where accurate measurements might otherwise be impractical.
- Can be used with a wide variety of special purpose transducers.

System C

- Thickness measuring element is specified by customer subject only to the requirement that it provide a compatible analog or BCD thickness output.

APPENDIX II

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APPENDIX III

PERSONNEL AND ORGANIZATIONS CONTACTED

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<u>Congressional State and Federal</u>

Deming Cowles
Office of the State of Alaska

Department of Natural Resources
Juneau, Alaska

Peggy Hackett
Office of the State of Alaska

Office of Senator Frank Markowski

Office of Senator Ted Stevens

<u>United States Government</u>

Dr. Charles Babbendreier
National Science Foundation

Capt. Jack Boller
Marine Board
National Academy of Engineering

W. Timothy Husen
Polar Research Board
National Academy of Science

Joe Jones
Minerals Management Service, Alaska

Robert Niblock
Office of Technology Assessment

Paul Sellman
Cold Regions Research and Engineering Laboratory

Rodney Smith
Minerals Management Service, Alaska

Gesa Thuronyi
Library of Congress

Dr. Ed Todd
Polar Programs
National Science Foundation

Rishi Tyaggi
Minerals Management Service, Alaska

Canadian Government and Academic Activities

Ralph Barer
Defence Research Estate, Pacific. F.N.O.

Dr. T. R. Chari
The Memorial University of Newfoundland

J. R. Eickmeier
National Energy Board

Dr. W. H. Erickson
Physical Metallurgy Research Laboratory

Dr. Brian Hope
Department of Civil Engineering
Queens University

R.E. Jackson
National Energy Board
Gas Pipeline Group

Dr. Alan Judge
Department of Energy, Mines and Resources

Fred H. Lepine
Department of Energy, Mines and Resources

Dr. C.A. Lewis
Department of Indian and Northern Affairs

Dr. V. M. Malhotra
Mineral Sciences Laboratory

Dr. E. Frederick Roots
National Research Council

T.H. Shwed
National Energy Board
Oil Pipeline Group

Dr. Raymond J. Smith
Department of Energy, Mines and Resources

Embassies

Mr. Lars Møller
Danish Embassy, Washington, D.C.

Mr. Bjorneby
Norwegian Embassy, Washington, D.C.

Ms. Judith Lowe
Canadian Embassy, Washington, D.C.

Mr. Slyfield
Canadian Embassy, Washington, D.C.

Norway/U.K. Government and Societies

Ken Paddock
Department of Energy, UK

Dr. David Partridge
Department of Energy, UK

Rune Sletten
Det Norske Veritas, Oslo, Norway

Industrial - International

Wade Abadie
Taylor Diving and Salvage, Inc.

Jerry G. Agi
J. Agi and Associates, Ltd.

Dr. George A. Alers
Magnasonics, Inc.

American Petroleum Institute
Washington, D.C.

D. Baran
OSEL Group, Ltd.

Denis Baudais
Panarctic Oils, Ltd.

Carter Beasley
AMF Tuboscope

Bill Belsey
Can-Dive Services, Ltd.

I V. Bodenberger
Magnetische Prufanlagen GmbH

Ray Brandt
Esso Resources Canada, Ltd.

C. Brook
Wells-Krautkramer, Ltd.

Capt. Francis Bruen, R.N. (ret.)
Underwater Security Consultants, Ltd.

Bob Colomy
Sub Sea International

Bennie Cox
Esso Resources Canada, Ltd.

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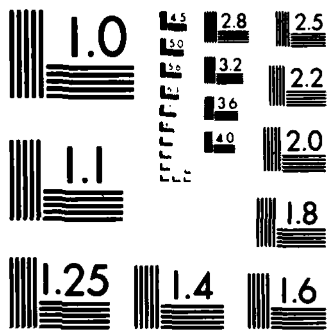

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Industrial - International (Continued)

K. A. M. Darling
Pantatron Systems, Ltd., UK

Jim English
Can-Dive Services, Ltd.

R. Mark Erlanson
Circle Chemical Company, Inc.,

Jerry Evans
Santa Fe Diving Services, Inc.

Ed Ferco
Dome Petroleum

Ken Fischer
Gulf Canada Resources, Inc.

D. Fissel
Arctic Sciences, Ltd.

Richard Frisbie
Solus Ocean Systems, Inc.

Andre Galerne
International Underwater Contractors, Inc.

R. Geer
Shell Oil Co.

Amos S. Greer
Southwest Research Institute

Bruce Heldstab
Taylor Diving and Salvage, Inc.

Carl Helwig
Sub Sea International

Henry Hicks
Taylor Diving and Salvage, Inc.

John Johnson
Oceaneering International, Inc.

Victor Kelly
NDT International,Inc.

Al Lancaster
Atlantic Diving Co., Inc.

Industrial - International (Continued)

J. Laury
Solus Ocean Systems, Inc.

D. Laxo
Standard Oil of California

Joseph H. Lehmann
Norton Corrosion, Ltd., Inc.

J. MacFarlane
International Submarine Engineering, Ltd.

E. Marino
Sub Sea Oil Services S.p.A.

Nick McMillan
Vetco Services, Inc.

J. Maybury
Wells-Krautkramer, Ltd.

D. Michel
Taylor Diving and Salvage Co.

Sandy Milne
Dome Petroleum, Ltd.

Wayne Nodland
Applied Physics Laboratory
University of Washington

Geoffrey Nunn
Brown and Root, Inc.

Phil Nuytten
Can-Dive Services, Ltd.

Brian Pearson
General Descaling Co., Ltd.

Jack Ramsdale
Atlantic Diving Co., Inc.

M.S. Reading
CORRINTEC/UK, Ltd.

Steve Reimer
Reimer Consultants

Caroline Richards
Honeywell Marine Services

Industrial - International (Continued)

Andy Robertson
AMF Tuboscope, Inc.

Carl Runge
Exxon Production Research

Ernst Scherholm
CanOcean Resources

Frank Sayle
Oceaneering International, Inc.

W. Searle
Searle Consultants

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Thorn EMI Electronics, Ltd.

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Sub Sea International

Bruce Sylvester
Sylvester Underseas Inspection

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Construction Industry Research and Information Association (CIRIA)

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MARTECH International

Brian Watt
Watt Association

Mr. Wenig
Magnetische Prufanlagen GmbH

Gary Wilton
Arctic Sciences

Frank Wood
Seaward Inc.

Peter J. Wood
Morgan Berkeley and Co., Ltd. (CORRINTEC Group)

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